Marine Visualization System: An Augmented Reality Approach

by

Eduard Cojoc-Wisernig
B.Eng.,M.Sc., Politehnica University of Bucharest, 2008
M.A., University of Bucharest, 2010
B.Phil., University of Bucharest, 2009

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Supervisory Committee

Dr. Brian Wyvill, Supervisor
(Department of Computer Science)

Dr. Bruce Kapron, Supervisor
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Dr. Eric Hochstein, Outside Member
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ABSTRACT

Sailboat operation must account for a variety of environmental factors, including wind, tidal currents, shore features and atmospheric conditions. We introduce the first method of rendering an augmented reality scene for sailing, using various visual techniques to represent environmental aspects, such as particle cloud animations for the wind and current. The visual content is provided using a hardware/software system that gathers data from various scattered sources on a boat (e.g. instruments), processes the data and broadcasts the information over a local network to one or more displays that render the immersive 3D graphics.

Current technology provides information about environmental factors via a diverse collection of displays which render data collected by sensors and instruments. This data is typically provided numerically or using rudimentary abstract graphical representations, with minimal processing, and with little or no integration of the various scattered sources. My goal was to build the first working prototype of a system that centralizes collected data on a boat and provides an integrated 3D rendering using a unified AR visual interface.

Since this research is the first of its kind in a few largely unexplored areas of technological interest, I found that the most fruitful method to evaluate the various iterations of different components was to employ an autobiographical design method.

Sailing is the process of controlling various aspects of boat operation in order to produce propulsion by harnessing wind energy using sails. Devising a strategy for safe and adequate sailboat control relies upon a solid understanding of the surrounding environment and its behaviour, in addition to many layers of know-how pertaining to employing the acquired knowledge.

My research is grouped into three distinct, yet interdependent parts; first, a hardware and software system that collects data with the purpose of processing and broadcasting visual information; second, a graphical interface that provides information using immersive AR graphics; and last, an in-depth investigation and discussion of the problem and potential solutions from a design thinking perspective.

The scope of this investigation is broad, covering aspects from assembling mechanical implements, to building electronics with customized sensing capabilities, interfacing existing ship's instruments, configuring a local network and server, implementing processing strategies, and broadcasting a WebGL-based AR scene as an immersive visual experience.

I also performed a design thinking investigation that incorporates recent research from the most relevant fields of study (e.g. HCI, visualization etc.) with the ultimate goal of integrating it into a conceptual system and a taxonomy of relevant factors. The term *interdisciplinary* is most accurate in denoting the nature of this body of work.

At the time of writing, there are two major players that are starting to develop AR-based commercial products for marine navigation: Raymarine (an AR extension of their chart-based data) and Mitsubishi (AR navigation software for commercial/industrial shipping). I am not aware of any marine AR visualization that is targeted at environmental awareness for sailboats through visualization (wind, tidal currents etc.) and my research constitutes the first documented and published efforts that approached this topic.

Keywords: *marine visualization, augmented reality, distributed system, information synthesis, abstraction model, autobiographical design, pseudo-natural visual appearance*

To Albert and Pam,

to Love,

to Life.

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I would like to acknowledge my colleagues from the Computer Science Department at the University of Victoria. In particular, Lucky and Robert Steacy, your feedback and assistance helped me time and time again.

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Most importantly, thank you Pamela, for Albert, for a life abundant in bliss and love and for the courage to put up with the roller coaster of adventures we have every day.

To Albert, whose coming into existence gave me the incentive for the final push to finish and defend.

"Believe me, my young friend, there is nothing – absolutely nothing – half so much worth doing as simply messing about in boats. Simply messing, he went on dreamily: messing – about – in – boats"

The Wind in the Willows
Kenneth Grahame

“Always make a definition or sketch of what presents itself to your mind, so you can see it stripped bare to its essential nature and identify it clearly, in whole and in all its parts, and can tell yourself its name and the names of those elements of which it is compounded and into which it will be dissolved.

Nothing is so conducive to greatness of mind as the ability to subject each element of our experience in life to methodical and truthful examination, always at the same time using this scrutiny as a means to reflect on the nature of the universe, the contribution any given action or event makes to that nature, the value it has for the whole[...]”

Meditations, Marcus Aurelius
Book Three, 11

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Chapter 1

Introduction

> "Difficulties are just things to overcome, after all."
>
> *Ernest Shackleton*

Every once in a while, a sailor, frustrated with the instruments and overwhelmed by the complexity of sailing, has that familiar thought in mind: "there's got to be a better way!".

Figure 1.1: Gypsy Moth IV, sailed single-handed around the world by Sir Francis Chichester in 1965

Throughout history, every so often, somebody has a hunch that turns out to be a good idea, for example, latitude-sailing using a sun-compass, like the vikings, or later, using a balanced magnetic needle to keep track of orientation at sea.

Improvements in clock-making, in conjunction with the use of a sextant gave us longitude. As a result, sailors started to have answers to the question "where are we?", that went beyond the sight of familiar surroundings. In a strict and literal sense, a representation of position and orientation is an adequate answer to this question.

Though, in a more accurate way, the answer is akin to an onion, wrapped in concentric layers of complexity and ultimately bound by only imagination itself.

In sailboat navigation, whether we are talking about that drying rock just outside the breakwater or the eye of a storm in open ocean, another important layer to add to the concepts of position and orientation is an understanding of the current surrounding environment.

The more we peel the various layers of knowledge needed to safely sail, the more we realize that there are actually only two questions that come to play: "where are we?" and "what's happening around us?".

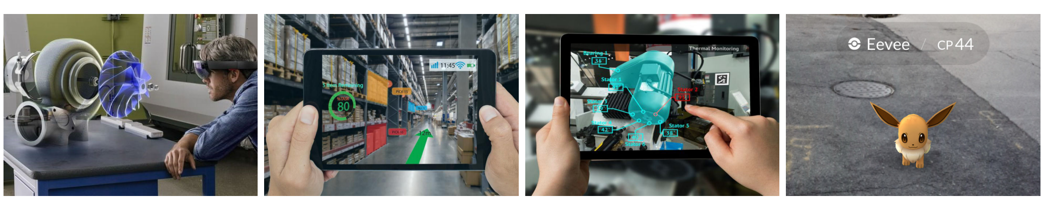
The purpose of my research is to push the boundaries of current technology in the quest for a unified answer to these questions.

1.1 Context

Augmented reality (AR) technology is on the cusp of triggering a massive paradigm shift in the way we use and understand computing and meta-information integration into every day life.

Over the last decade we have seen increasing interest in AR hardware research. Prototypes, such as Google Glass or Microsoft HoloLens, captured the hopes and dreams of many software developers and visionaries.

AR technology has been a hot research topic for several decades, yet over the last few years it has started to transcend academia and cross into the commercial domain with the first generation of product offerings. These are almost entirely focused on indoor AR experiences, particularly after the



(a) (b) (c) (d)

Figure 1.2: Some examples of AR applications: (a) Product design using OST HMD, (b) Navigation using VST handheld, (c) Part description using VST handheld, (d) Pokemon Go game using VST handheld.

collapse of the Osterhoutgroup earlier this year.

Initial AR head-mounted display (HMD) (Figure 1.2a) products received mixed reviews when they were first introduced, but since their launch, several other companies have joined in and recently we have seen a boom in AR glasses at affordable prices. Other non-HMD AR applications have also become popular, with Pokemon Go (Figure 1.2d) being an example of an application that provides AR content on a handheld device, such as a smartphone or a tablet, without requiring any specialized hardware. AR navigation and service/manufacturing applications have also seen extensive research and product development (Figure 1.2b and 1.2c, respectively). A quick distinction to be made is between video see-thru (VST) devices and optical see-thru devices (OST), where the visual feed comes from a camera in the former and directly from the eyes in the latter [1].

Sailing, i.e. operating a boat that uses sails for propulsion, is another major focus of my research. The process of sailing requires sailors to be aware of the wind, the shore, tidal currents, wildlife, sail geometry, drift and many more aspects. Fortunately, there are instruments that can help acquire data from several sources: wind direction and strength from the anemometer, water depth from the depth sounder, navigational information from the GPS chart-plotter and others. Even so, sailboat operation is a challenging and demanding task even for experienced sailors. The marine environment is unforgiving and hostile towards electronics, which can be seen in the delayed adoption of commonplace electronic systems such as GPS navigators. Electronic devices that operate in the marine environment need to be built to rugged standards [2]. It is for this reason that, at the time of writing, there is no AR HMD suitable for marine use available either as a commercial product or even in experimental development.

(a) (b) (c) (d)

Figure 1.3: (a) Latest generation GPS chart-plotter, (b) Chart-table instruments, (c) Typical cockpit instruments, (d) High-end bridge.

Another aspect that may be related is the fact that the 2D paradigm in which marine information is displayed in even the most advanced recent chart-plotters resembles GPS car navigators from 20 years ago (Figure 1.3a). Also, the prohibitively high cost for marine electronics determines a slow rate of adoption of new technology; in fact, most sailboats from the last few decades still operate with the original instruments they were outfitted with (Figure 1.3b, 1.3c).

Even on a more advanced and modern bridge, like in Figure 1.3d, we find the same digital chart-plotter and numeric display instrument styles that were used for at least a couple decades. It is, therefore, not surprising that there are few academic research efforts that we know of that approach the idea of extending AR technology to address marine navigational and environmental awareness.

Before I talk about the needs of sailors from an informational perspective, let's first look at a few existing ideas for developing aids to navigation using an AR paradigm. Car manufacturers were early adopters of advancements in AR technology and there have been some remarkable developments as a result. In Figure 1.4a we see an early AR scene with a correlated perspective of the real and virtual environments, where the information is coming from the GPS sensors and displayed with a simple path representation. Figure 1.4b adds a layer of complexity by incorporating data regarding the distance to nearby vehicles, using sensors and computer vision methods. The simulated concept AR scene from Figure 1.4c shows the scenario of vehicular visualization in a self-driving car. The closest any AR application has gotten to the marine environment came in the form of the TV visualizations used for the America's Cup (Figure 1.4d) [3].

Due to the structured and heavily regulated environment they operate

(a) (b) (c) (d)

Figure 1.4: AR scene: (a) path overlay, (b) distance awareness overlay, (c) self-driving car visualization, (d) America's cup visualization

in, drivers have fundamentally different needs than sailors [4]. In fact, the earliest examples of a rudimentary form of AR comes from the use of heads-up displays (HUD) in jet fighters (Figure 1.5a) [5]. This kind of immersive display was subsequently adopted by the civil aviation industry (Figure 1.5b). Figure 1.5c shows a modern approach, using a sophisticated AR scene. By this point we start to realize that there is definitely potential in investigating the use of AR technology to develop navigational assistance applications. So, the imminent question is, can we use a similar approach for sailboat navigation and environment awareness?

Further, should we?

The short answer to both questions is ”yes,” and the long answer is the remainder of this document, starting with the problem statement in the following section and continuing to explore a series of aspects pertaining to finding a path towards potential solutions.

1.2 Problem

The problem I address in this research is the inherent difficulty of sailboat operation arising from the complexity of disparate sources of data requiring varying levels of attention, processing and interpretation, and the need for real-time decision-making based on this data.

I will explore whether it is possible to process and display data regarding a boat’s operation and immediate environment in a form that is more immediate and convenient than that provided by the existing paradigm of multiple instruments and pure sensory processing by the sailor (Figure 1.6).

In the context of pure sailing, sailors of small sailboats learn to gauge

(a) (b) (c) (d)

Figure 1.5: HUD: (a) early jet fighter, (b) commercial aviation, (c) modern AR bridge concept, (d) HMD AR engine inspection

things like current and wind speed through all kinds of intuitive visual and bodily cues (e.g. the feel of the swaying of the boat, visual cues from the appearance or movement of the waves, etc.)

There are, however, all kinds of information that may be relevant to the sailor which are not intuitively available in this way (e.g. obstructions under the water, potential shifts in atmospheric conditions, subtle changes in pressure, etc.)

Sailors working on larger sailing vessels are less able to navigate by feel in the same way. They compensate by using various kinds of instruments which can display things like wind speed, air pressure, current direction, etc.

The problem is that each of these readouts in isolation can be misleading.

Looking at air pressure by itself, or current direction by itself, or wind speed by itself, ignores the ways in which these features interact. In order to sail effectively, sailors must be able to calculate the complex causal interplay between these features and how each feeds into the others. Having the information displayed on readouts in this way can be unintuitive, difficult to track, and cognitively taxing on sailors who must attempt to integrate them mentally.

1.2.1 The Immediate Environment

In broad strokes, safe sailing relies on the process of controlling the operation of a boat while constantly seeking answers to two fundamental questions:

1. What is happening around us?

2. Where are we?

If we're talking about sailing vessels in particular, the fact that sails are used to harness the power of the wind for propulsion implies an increased necessity for an astute awareness regarding the behaviour of the wind.

Because of natural limitations of traditional sailboat hull designs (i.e. displacement hull), sailboats are slow, especially when compared to other vehicles [6]. Sailboat displacement hulls have a predefined maximum hull speed, which cannot be surpassed, no matter how much force the boat can produce; this is due to the fact that the boat starts climbing its own bow wave.

$$Hullspeed \approx 1.35 * \sqrt{Lengthofwaterline}$$

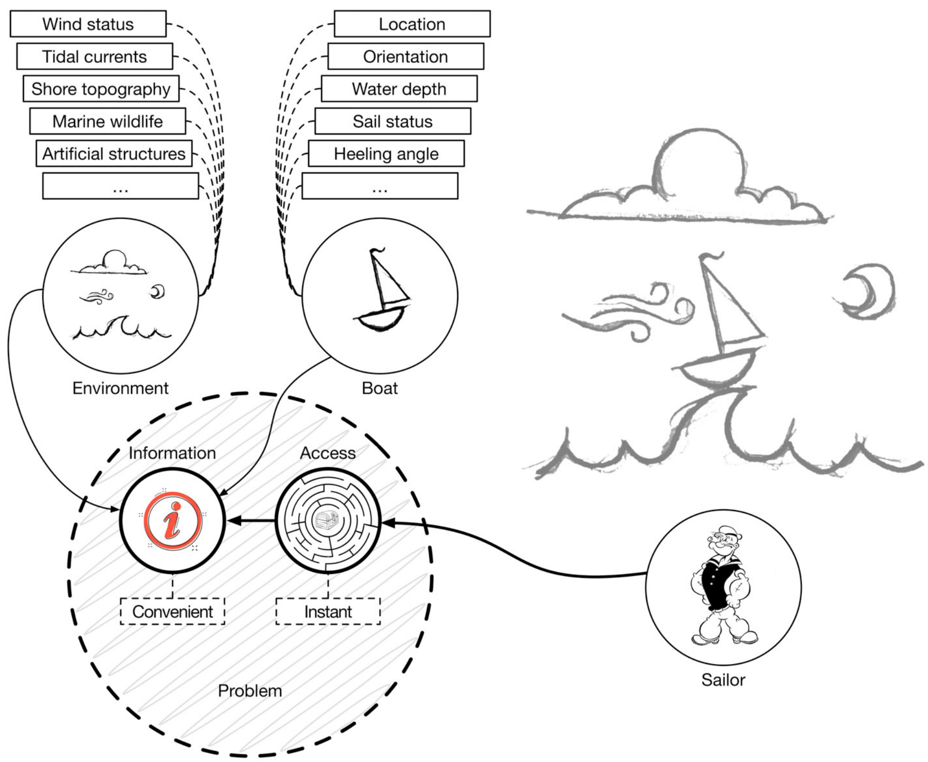


Figure 1.6: Problem overview

The hull speed of a typical sailboat around 35ft in length is approx. 7.4kn (13.7km/h), which is comparable to the tidal currents speeds commonly found on the west coast of Canada[1]. So, it is quite common for sailors to pay close attention to what the tidal currents are doing.

Hitting rocks or reefs can easily turn into a catastrophe, so another important aspect of safe sailing is to be aware of the position, orientation and motion of the boat relative to known threats. Having access to information regarding the shore topography is, therefore, paramount, either in the form of navigation tools (e.g. paper charts, digital chart-plotters etc.) or by relying on memory and experience.

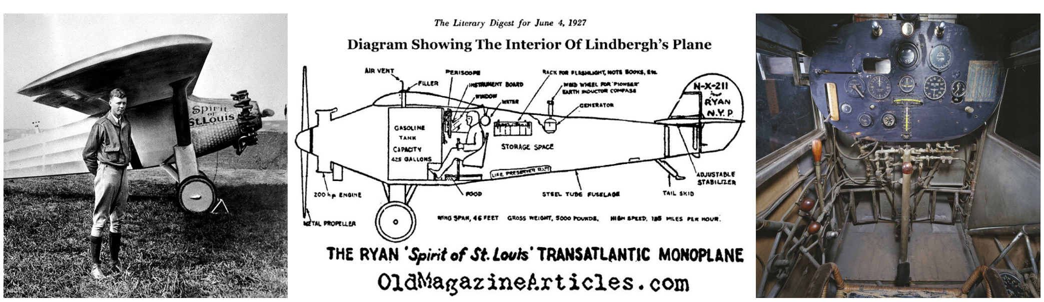
In addition to these important aspects, there are several others that need to be constantly monitored, such as local boat traffic, marine wildlife, artificial structures, aids to navigation or floating debris.

1.2.2 The Sailboat

Everything I've mentioned so far is part of a boat's environment. There is another major source of information that needs to be monitored and that is the boat itself and all of the various subsystems it features.

Before I examine the details of a sailboat system, let's first look at another kind of vehicle: the airplane "The Spirit of St. Louis." Charles Lindbergh

[1]The highest currents commonly encountered are more than twice the maximum speed of a regular size sailboat. For example: Skookumchuck Narrows - 17.7kn, Nakwakto Rapids - 18kn, and the notorious Seymour Narrows (15kn), which was described by Captain Vancouver as "one of the vilest stretches of water in the world."



(a) (b) (c)

Figure 1.7: Spirit of St. Louis: (a) outside view, (b) diagram, (c) cockpit

flew this famous airplane in 1927 on the first solo, nonstop transatlantic flight (Figure 1.7a). The internal distribution of space inside the plane was focused on prioritizing the location of the main tank that carried a massive volume of fuel relative to the weight of the plane (Figure 1.7b). This made for a rather peculiar cockpit design, which didn't have any forward facing windows. Instead, there were two small side windows and a retractable periscope, which offered extremely limited visibility. The forward facing part of the cockpit was basically a sheet of plywood with rudimentary instrumentation (Figure 1.7c).

Figure 1.8: Foredeck in heavy seas

The reason I am mentioning this particular and unusual vehicular design feature is to highlight the fact that even though the amount of information available to Lindbergh was minimal, he, nevertheless, achieved a spectacular feat: crossing the Atlantic ocean nonstop. The point I am making is that every vehicle has its own needs regarding the scope of awareness the operator must face, even if some features may seem highly unintuitive, like having the visual awareness capabilities heavily restricted.

In strong contrast, sailboats require sailors to be able to visually monitor countless components, including sail position and condition, running rigging obstructions, wind indicator, tangled lines and standing rigging condition, just to mention a few entities outside of the cockpit (see Figure 1.8).

Inside the cockpit, there are typically various instruments that provide information about the status of the boat (e.g. engine control panel), as well as several devices that control the boat, with the most important being the helm (i.e. steering wheel or tiller). The most important source of information for sailors is usually found either in front of the steering wheel or mounted

Figure 1.9: Typical cockpit with instruments

into the outside of the companionway bulkhead in the form of a bundle of instruments connected to sensors embedded into the boat's systems. The most common instrument configurations include an anemometer (wind sensing), depth sounder, impeller log (speed over water), magnetic compass (orientation) and others (Figure 1.9).

One of the most important instruments and the tools sailors probably use most often is the GPS chart-plotter (location). Sometimes mechanical gauges can be attached to provide information, like atmospheric pressure or heeling angles.

1.3 Solution

I propose creating a system that integrates all this information together for the sailor and display that information in a centralized location (Figure 1.10).

One effective way to do this is to simplify the information delivered to sailors. I can provide overly simplistic, abstracted, or idealized, representations to the sailor to avoid information overload. This solves the problem of cognitive overload on sailors, but it introduces a new set of problems: if I simplify or idealize the information presented to sailors, then they are no longer acting on accurate information. Instead of correct information about their environment, they now have overly simplified accounts. Easier to understand, but far more dangerous if the sailor confuses the idealizing and simplifying assumptions for real facts about the world.

Bad choices can suddenly lead to disaster. The correct and more accurate

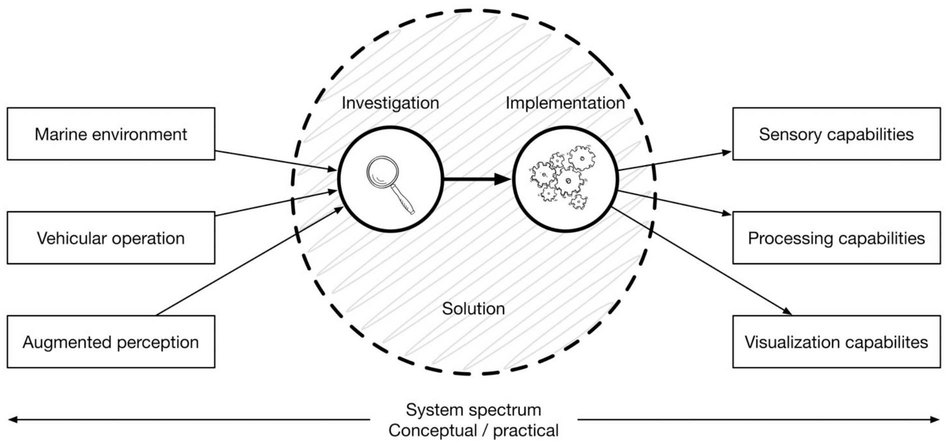


Figure 1.10: Solution overview

information needs to be available for sailors to use, but presenting this information intuitively requires idealizing and distorting it. It appears I must make a trade-off between models being understandable and being accurate.

Therefore, in order to balance all of these concerns, I need an approach that conveys a lot of different kinds of information to sailor in a way that is more intuitive than just a collection of different numerical readouts, but which also provides a greater variety of information than can be gained from pure sailing.

This information must be integrated to relieve sailors from the strain of interpreting it from the sailor.

I need to represent the information in a simplified and intuitive manner which will require distorting and idealizing what is presented to the sailors, while at the same time not misleading them so that they cause accidents.

Lastly, I also need to make sure that the more accurate (but less intuitive) numerical information is still available to sailors in case the more intuitive representation is insufficient for their needs.

My approach towards finding a solution is at the intersection of several fields of academic study, which will be grouped into a two-part solution: implementation and investigation.

The aim of the implementation part of the solution is to design, build, and test out sensory, processing, and visualization capabilities. Given the experimental nature of the solution and the absence of previous work to build upon, the process involves several iterations and prototyping phases, whose success or failure needs to be evaluated and reintegrated into the conceptual model at each step.

The aim of the investigative part of the solution is to acquire facts and observations relating to the research problem, to generate insights into the various disconnected entities under scrutiny, and ultimately, to conceptually join these entities together into a unified abstract model, as part of the conceptual side of the system. Some of the most important aspects under investigation are a general understanding of the elements that come to play in vehicle operation, and particularly pertaining to the marine environment, as well as a thorough mapping of various perception-related concepts and theories. This model is a complex web of connections between relevant, yet disparate aspects of the problem and it serves as the blueprint for subsequent efforts to implement practical features.

1.4 Objectives

The overall aim of this dissertation is twofold:

1. To design and build elements of a prototype AR-based visualization system that aids in the navigation of a sailboat (Figure 1.11).

2. To use an investigative method inspired by design-thinking that covers the in-depth analysis of the problem as well as the transition into principles and subsequently into system features.

The first aim is of a scientific/technological nature, featuring the following objectives:

- To identify, classify, and analyze the factors, entities and processes that come to play in the process of sailing (e.g. wind, sail trim, currents, navigation, etc.);

- To propose a model of the complex relationship among the entities mentioned above;

- To design a system that augments sailors' understanding of the environment and their boats' operation (see Figure 1.11);

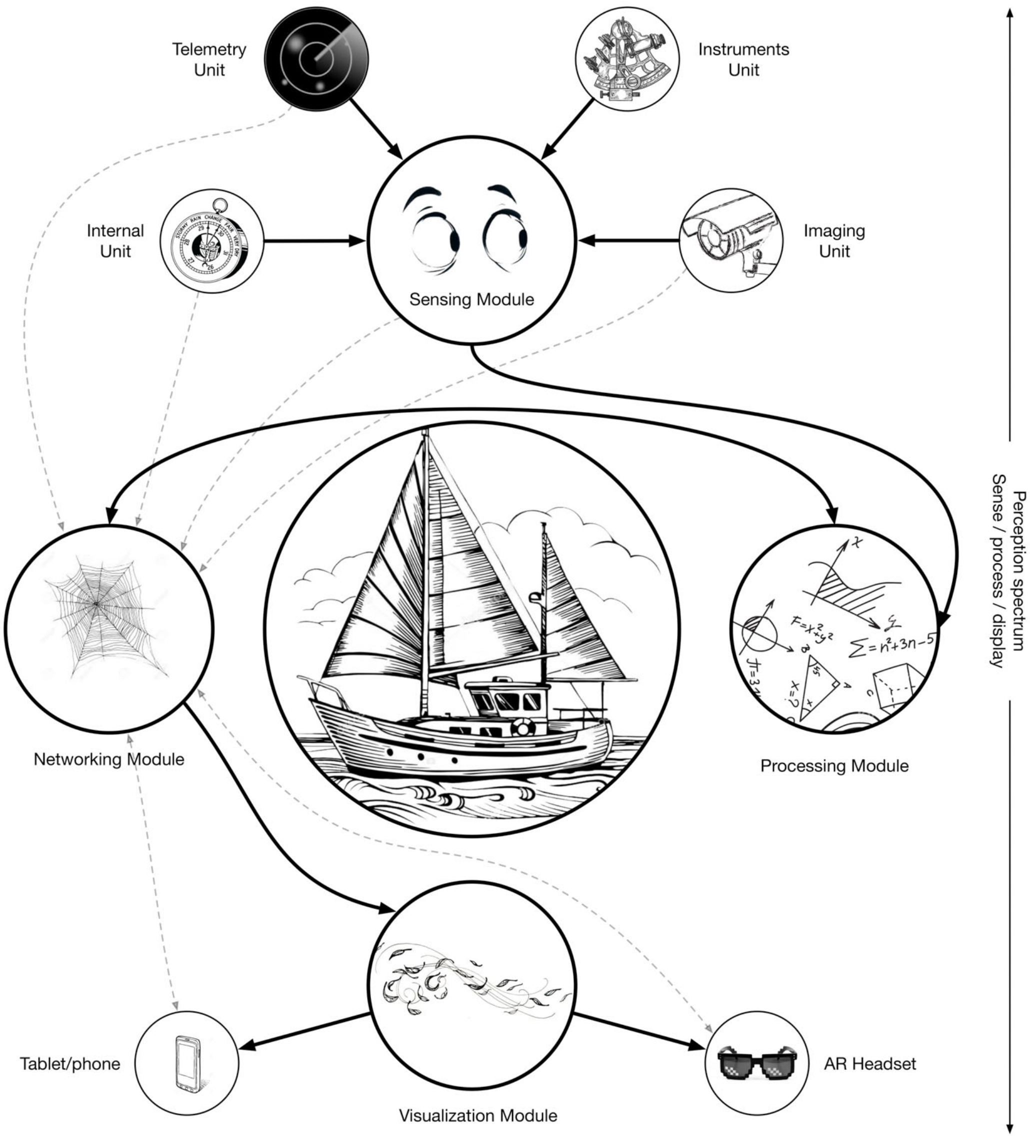


Figure 1.11: System overview

- To build mechanical implements, electronic components, a network, a visual interface, etc.;
- To create a model to present visual content as part of an augmented reality scene.

Our second aim is of an eclectic nature with some of the most significant objectives being:

- To explore a diverse palette of perception, modelling, and abstraction considerations that affect the way we understand and use visualization tools;
- To investigate the meaning of information representation, particularly that of non-visual entities being represented visually;
- To devise a methodology of inquiry into the causes and explanations of relevant phenomena;
- To outline a method of keeping track of the decision-making pipeline, starting with facts and observations, continuing with insights, conceptual and design principles, and finally resulting in actual features.

1.5 Contributions

Considering that the field of AR vehicular visualization is still in its infancy, I investigated and, where possible, filled in some of the major aspects that determine the foundation upon which this field of study relies, in particular pertaining to its use for the purpose of marine visualization.

List of contributions:

- ☐ **C1.** A vehicular visualization system featuring a network of devices, instrument interfaces, imaging capabilities, sensor readings, processing and broadcasting capabilities (Chapter 5)
- ☐ **C2.** Telemetry and internal units featuring an array of sensors not commonly present on sailboats (Sections 5.2.1, 5.2.4)
- ☐ **C3.** A WebGL-based immersive AR interface (Section 5.5)

- ☐ **C4.** An AR scene featuring entities that correlate with geo-physical phenomena from the sailing environment (Chapter 6)
- ☐ **C5.** A method of investigating entities and aspects vital to the process of sailing (Sections 7.3.1, 7.3.2)
- ☐ **C6.** An interaction/correlation model for these entities (Section 7.7)
- ☐ **C7.** A discussion on the nature of these entities and of suitable potential visualization approaches (Chapter 6)
- ☐ **C8.** A design recount of the process of interface development inside the AR paradigm, focused on marine vehicular visualization (Chapter 7)
- ☐ **C9.** A graph-based flow matrix that keeps track of the extensive number of inter-dependencies between observations, insights, principles, and features (Section 7.7)
- ☐ **C10.** An in-depth analysis of the particular elements that comprise feedback loops in the process of sailboat operation, in three different scenarios (Chapter 3)
- ☐ **C11.** A recount of the preliminary design process in three phases or iterations (Chapter 4)
- ☐ **C12.** A classification of different potential layers of abstraction for sailing phenomena (Section 6.4)
- ☐ **C13.** A discussion about the potential of using visual aids to achieve contextual visual awareness (Sections 6.4.5, 6.4.6)

1.6 Dissertation Organization

Related Work

In the related work chapter I examined the foundational background against which many facets of our research is set. I examine the concepts behind virtual environments and few a notable examples. Then, I explore the concepts of augmented reality and augmented perception.

Background

This chapter begins with a brief introduction of the most important aspects of the process of sailing. First, I discuss terms that are relevant to my field of research. Then, I continue by looking into the different points of sail. Afterwards, I discuss the main topic of this chapter: the feedback loop, which is a way to formalize the interaction between sailors and their boats/environment. Last, I identify and cover three different sailing methods and discuss how sailors' cognitive processes are determined by the type of feedback loop they employ.

Preliminary Designs

In this chapter we see a chronological and conceptual map of how I got to this final point in our research. After covering the background against which this project has started, I look at the preliminary investigation of the subject matter. Then, I explore the creation of the first prototypes and ultimately evaluate those. The last section follows the impact of the lessons learned and how these changed my understanding of the problem at hand.

System

In this chapter provides detailed descriptions of all the major engineering components, classified as modules and units (Figure 1.11. The sensing module performs real-time data acquisition from a wide range of sources: telemetry unit, imaging unit, instruments unit, internal unit. The networking module covers the details such as the topology of the network as well as the devices and protocols used. The processing module gathers data, logs it, processes it, and broadcasts it. The visualization module section covers various aspects about way the system provides access to the visualization content (devices, software, and interface details).

Visualization

The visualization chapter is a detailed recount of the structure of the scene used to display the AR content. It starts with detailed descriptions of the entities used and finishes with a discussion of the visualization choices made in the development process.

Solution Analysis

This chapter identifies and correlates all of the aspects that determine the implementation choices I made. In sequence, I cover observations, insights, conceptual principles, design principles, and, finally, features. In addition to identifying and discussing intimate details that take important roles, I build a flow matrix by tracing a network of conceptual dependencies.

Annex A, Sea-trial Report

This annex is a recount of one of the sea-trials I performed. It features a description of the objectives and goals of the sea-trial, a track of the route taken, a list of invaluable observations, and a detailed transcript of the notes I took at sea.

Annex B, Observations

In this annex I describe a series of observations I collected over time. They are literal transcripts of the thoughts people had when asked about the system. They are not sorted by any criteria and some of them became the basis for insights, while some others did not.

Chapter 2

Related Work

The current chapter works on two fronts, both as an introduction to the major concepts that are specific to my field of study, and also as a recount of significant research activity that shares some conceptual resemblance to my research project.

At the time of writing, the topic of real-time visualization of marine aspects using an Augmented Reality paradigm with the particular application of creating an interface that aids in vessel navigation is largely unexplored.

There are, however, a few projects that target the topic of autonomous ships. There is some noteworthy overlap, despite the fact that these projects are aimed at industrial-scale, commercial shipping in contrast to my focus on recreational vessels and, particularly sailboats.

From a commercial perspective, there were two noteworthy products launched in 2019, the Raymarine Axiom Enhanced Awareness and the Garmin Nautix. These two products approach the topic of AR visualization for the recreational boating market. However, I could not find any peer-reviewed academic papers about either product at the time of writing.

2.1 Early Virtual Environments

My research relies on the paradigm of augmented reality (AR) visualization. To understand AR, we need to first explore a couple fundamental aspects such as virtual environments and the virtuality continuum.

The concept of a virtual environment is preceded by that of presence. According to Slater and Wilbur, “Presence is a state of consciousness, the [psychological] sense of being in the virtual environment". [7]

Presence itself is a subjective concept, seen as "when the multimodal simulations (images, sounds, haptic feedback, etc.) are processed by the brain and understood as a coherent environment in which we can perform some activities and interact." [8] In this context, the concept of a virtual environment is used as a medium to provide the user with meaningful information.

Even though the terminology and the concepts I employ are relatively recent, we can find instances of virtual environments going back tens of thousands of years.

One of the earliest examples I found is the complex collection of paintings on the walls of the Chauvet Cave dated around 35,000 BC [9].

Figure 2.1: Chauvet Cave Rock-Art

In the book "The archaeology of rock-art", Chippendale gives us an idea about the immersive nature of the experience of being exposed to this kind of art form. [10] Wavering light is produced by torches, hearths, or bonfires and is projected onto the walls to create the impression of animation (see Figure 2.1). Even more, there is an element of interactivity as the scene comes to life while the user walks around, changing the perspective.

A similar, though much more recent virtual environment (VE) can be experienced in the Vatican's Sistine Chapel (see Figure 2.2) where visitors find themselves immersed and overwhelmed by an abundance of visual stimuli that portray an overarching story line.

From these two examples, however, it would be erroneous to assume that any work of art is a VE, since there are several characteristics that are re-

Figure 2.2: Sistine Chapel, Vatican

quired for it to qualify, with immersion and presence being two of the most obvious.

A major breakthrough that contributed to a widespread change in the nature of art and subsequently a precursor to virtual reality came in the form of Wagner's aesthetic concept of gesammtkunstwerk[1] [11]. According to Koss, the "Gesamtkunstwerk, as conceived by Wagner, [...] retained the specificity of the single discipline but enforced its strength through an interdisciplinary collaborative effort." [12]

In the book "The Total Work of Art: From Bayreuth to Cyberspace", Smith [13] sheds light on how, guided by this ideal, Wagner's later operas attempted to create a harmonious fusion between the various media typically encountered in this art form, including the music, libretto style, story plot, stage effect and setup, and choreography. By contrast, contemporary rival composers were portrayed by Wagner as employing celebrated bravura singing, sensational stage effects, and meaningless plots, resulting in a dissonant experience [11]. Towards the end of the 19th century, Wagner pioneered an experimental, one-off opera house[2] with exceptional acoustics and designed to enhance the audio-visual operatic experience, where the orchestra pit was invisible to the audience [14]. The aim of this endeavour was to provide users with a focused experience where non-essential aspects were purposely hidden.

In the early 20th century there were a few experiments in static stereography as the audio-visual technology progressed.

From a graphics perspective, the world's first computer art, dated around 1956-1958, was a rendered glowing image of a pin-up girl on a military IBM computer: "The pin-up image itself was programmed as a series of short lines, or vectors, encoded on a stack of about 97 Hollerith type punched cards" [15] (Figure 2.3).

It was in the 60's, however, when the interest in immersive experiences was met with new advances in technology that triggered a whole wave of scientific inquiry into what we today call Virtual Reality (VR).

In 1962 the cinematographer M. Heilig built a multi sensory vehicle simulator called Sensorama, (see Figure 2.4) which users could experience not only stereographic video, surround sound, and haptic feedback, but also air-

[1] Gesamtkunstwerk could be translated and understood as a total (or complete) work of art

[2] Bayreuther Festspielhaus

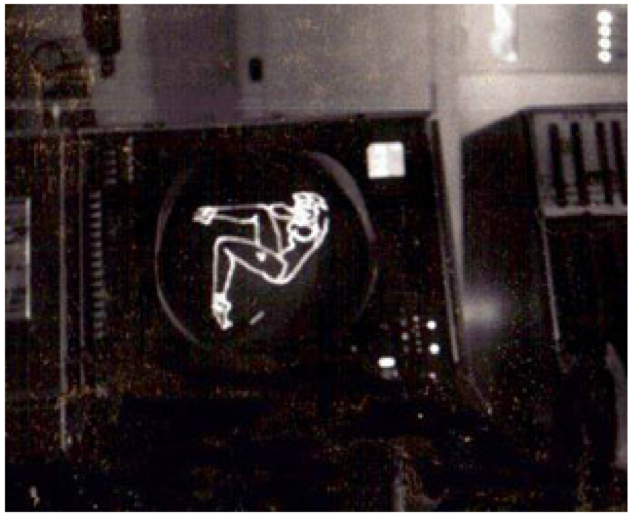


Figure 2.3: World's first computer art

flow generated with fans, and even smells. [16] In this early VR precursor, the user had no control over the experience, but was fully immersed in it.

Figure 2.4: Sensorama

Around the same time, I. Sutherland started working on a research project involving the first application of computer aided-design, Sketchpad [17], which was also the first program ever that featured a graphical user interface. Human computer interaction had been in use for several decades at that time, but none of those early approaches used a graphical medium.

The infamous 1965 article entitled "The ultimate display", published by Sutherland [18] serves as an invitation to explore the potential of future technology; it makes a case for the use of keyboards and hints at pointing devices such as joysticks, as well as approaching topics such as computer rendering and display types. This article is considered to be the first instance of the concept of VR being presented as a potentially achievable technology.

At this point, it is noteworthy to ponder on the meaning of the term *display*, particularly since today's understanding of the term may overshadow

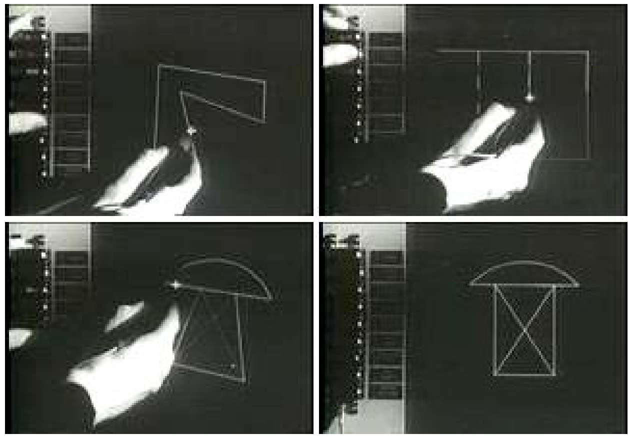


Figure 2.5: Sketchpad

some of its broader original meaning and conceptual potential.

The Merriam-Webster dictionary defines the verb *to display* as:

> display (verb)
> :to make evident
> :to exhibit ostentatiously

From an engineering perspective, one could argue that a display may take the form of any technological means that can produce a representation of deliberate content, with notable examples being Sensorama's olfactory features and wind simulation using fans.

Even more so, in the above mentioned paper [18], Sutherland goes as far as proposing a display that could alter matter itself, much like the Holodeck concept seen in Star Trek.

In 1967, F. Brooks started Project GROPE, that would span several decades. This project investigated how haptic displays would improve users' understanding of the virtual content [19].

Sutherland's further research into head-mounted displays (HMDs) from 1968 featured the first truly immersive stereographic interactive system; the technology of HMDs has never stopped evolving since [20].

2.2 Marine Applications

Advances in vessel-based sensor technology, better ship-to-shore communication connectivity, and increases in vessel traffic necessitated advances in automation for maritime navigation. Data fusion, including integration of ship-based data, electronic charts, and remote sensing data, such as satellite [21] and coastal RADAR offer new possibilities for enhanced safety in navigation. Initiatives such as the "Chart of the Future", which aims to enhance paper charts by incorporating bathymetry and shoreline imagery have been in development for over a decade [22]. Despite these technological advances, navigation, especially aboard small vessels, is often still done with paper charts and relies on human interpretation of sensor data.

Many systems have been introduced for enhanced visualization of sensor data, yet I am not aware of the existence of any augmented reality visualization interfaces designed exclusively for operators of small sailing vessels, either in academia, in industry, or as a commercial product. I will briefly describe a few existing systems below.

The problem of interface design for ship bridge operation is addressed in [23]. In this work, the author explores several aspects for integrating more and more navigation systems such as the ARPA/ECDIS. Our system builds on the existing 2D interface attempts by introducing an augmented reality interface.

As of early 2015, Rolls Royce [24] announced its intention to develop an augmented reality based interface for controlling various aspects in the command, navigation, and operation of cargo ships. The company released a design concept to the press, however, no articles or research reports have been published yet.

The open-source navigation software OpenCPN (as well as several other commercial products) has among its features a plug-in called Dashboard, that successfully integrates and displays NMEA-available information in a minimal 2D window system. While this plug-in approaches the same problem, displaying information from NMEA sensors, it does so in a 2D windowed paradigm, using a rudimentary 2D geometric and numeric approach. In my approach, I process the same data and render it as animated 3D layers in an augmented reality system.

A similar system based on augmented reality visualization for vehicles has been implemented on cars for a study with seniors [25]. The work is different from ours because it is focused primarily on creating an artificial environment, rather than augmenting the perceived reality. From this source, I learned about an interesting approach to mixed reality. Another paper described the research effort of a team using a simulated augmented reality windshield display to aid seniors in driver navigation [26].

Some of the benefits and flaws of augmented reality systems that are common with this project have been discussed at length in a survey from 2009 [27]. An interesting project from the Columbia University explores the potential to use augmented reality technologies to evaluate the potential benefits of using AR for armoured vehicle maintenance [28]. Its focus is primarily on the identification of different controls inside a tank, which could be applied to the interior of a sailboat (e.g for reading tank levels or engine RPM) at a later stage in our project.

Due to the rough nature of the marine environment, many aspects have to be taken into consideration for achieving the required level of ruggedness and reliability. In an interesting paper from 1999, the authors mention the challenges of making an AR system work in a rough environment [29] and most of the identified technological limitations are still valid today.

While these limitations still stand 20 years later, ruggedized versions of devices such as smartphones and tablets can serve as steppingstones towards bringing augmented reality visualization into rough environments.

The above mentioned research projects, together with the commercial AR products mentioned at the beginning of the chapter, offer a glimpse into the vibrant beginnings of a trend that tries to use AR in different ways for navigation.

2.3 Augmented Reality

Head mounted devices (HMDs) have been a research topic ever since I. Sutherland's initial research in the 1960s, yet the first efforts towards using an HMD in direct relation to elements of the real world have started around the early 1990s.

In [30] a 1992 article, Tom Caudell introduced the term "Augmented Reality:"

> "The enabling technology for this access interface is a heads-up (see-thru) display head set [...], combined with head position sensing and workplace registration systems. This technology is used

> to "augment" the visual field of the user with information necessary in the performance of the current task, and therefore we refer to the technology as "augmented reality" (AR)."

The following year, A. Janin continued the research in a paper [31] that further discusses the problem of calibrating the system.

One of the first approaches towards identifying the various degrees of mixed reality can be seen in P. Milgram's paper from 1994 [32]. In this article we get a first glimpse at the mixed reality spectrum.

In Azuma's 1999 paper [29], we find one of the first in-depth surveys of augmented reality research and terminology.

Starting with the early 2000s, we saw an increase of AR research projects, with AR Quake, outdoor augmented reality system [33] being a most prominent example.

In a paper from 2014 [34] entitled "Towards the Holodeck" the authors explored the potential use of a virtual reality environment for the purposes of visualization of scientific and engineering data. They also approached the issue of interactivity and proposed a scenario where a boat designer used a VR system to aid in understanding the spatial distribution of various features on a ship.

One of the earliest portrayals of the idea of VR being used for vehicular control is from the original Alien [35] movie. It also features as a great opportunity to showcase the potential for VR to be used as Augmented Reality as well, as in Figure 2.6.

In a paper from 2010 [36], the authors examined a few approaches to using AR technology for marine navigation purposes. They look into various topics, including fusing satellite photos with nautical charts, a vision system, and a discussion of using AR for marine applications. The considerations published in this paper are rather general, despite several figures illustrating commercial ships.

Another related paper from 2014 [37], focused on the issue of navigational awareness for large ships. The authors proposed an AR interface that integrates different kinds of data (GPS, AIS, wind etc.)

In one of my own papers from 2015 [38], I presented an early attempt to use an augmented reality system to visualize essential sailing information. The initial work sparked a related research project [39] that looked into using computer vision to identify debris in the video feed and to issue warnings using the display.

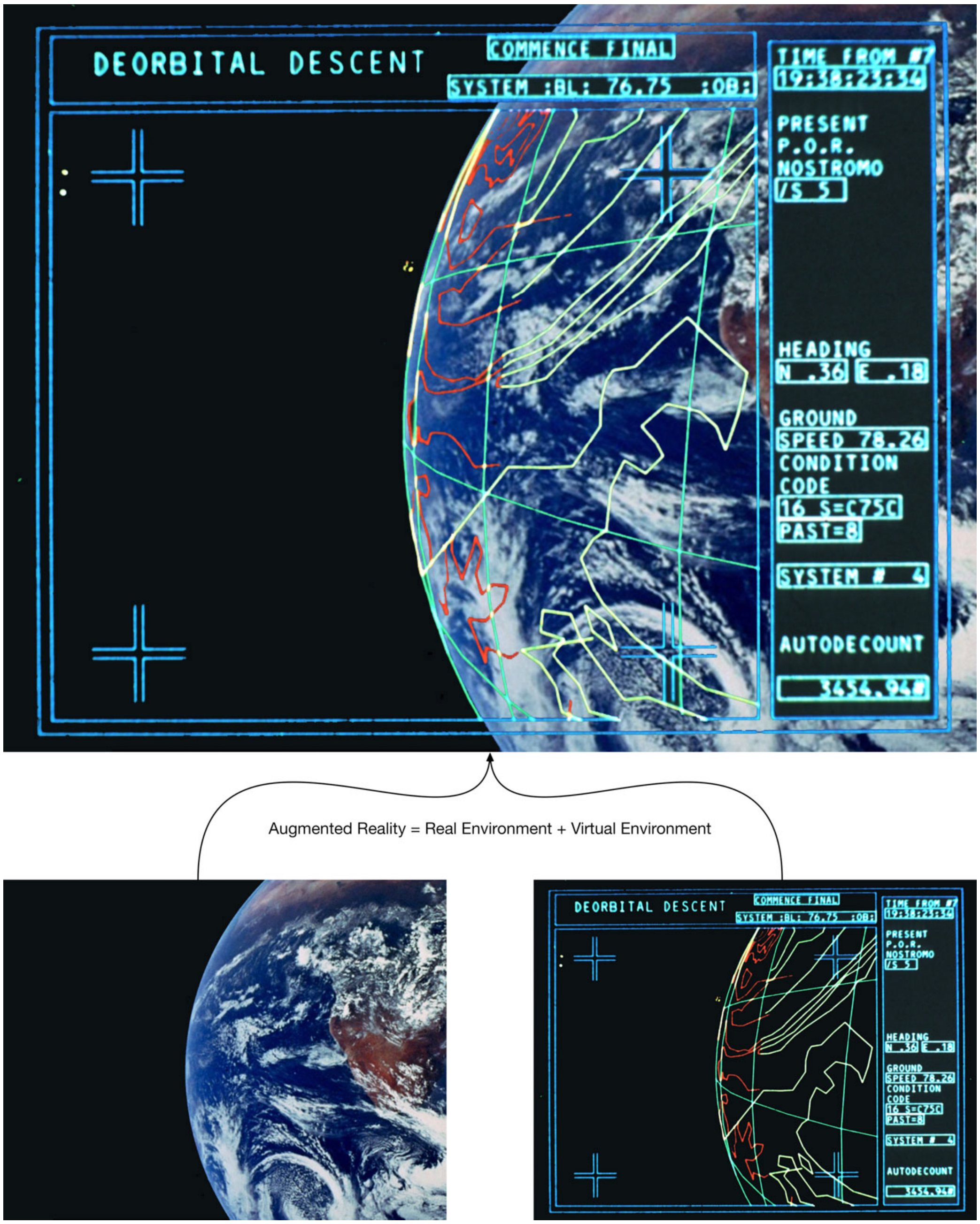


Figure 2.6: Early Concept of an Augmented Reality Vehicular Interface

Beyond our main focus on vehicular AR applications, the field of research surrounding augmented reality has seen a veritable explosion of interest over the last 10 years. While not directly related to my research project, the following papers provide a context of recent research in AR research that can be applied to my research endeavours.

The current approaches to extended reality (which includes AR and VR) have some serious limitations due to the input methods used such as the well established voice recognition, keyboards, or pointing devices. In a project from 2017, a promising alternative [40] comes in the form of electroencephalography interfacing, which facilitates real-time mental selection using tools commonly found in the medical sector.

A paper from Microsoft research published in 2015 [41] explored the capability of the Hololens not only to perform the typical functionalities of a HMD, but also to broadcast the visual experience to other users over Skype on regular displays. Another similar project, JackIn (2014) [42] used the live video feed from a HMD to construct a broader visual context for a spectator who observes a traditional 2D display.

Also on the topic of remote collaboration, this journal paper from 2014 [43] discussed potential ways to achieve collective, world-stabilized annotations for virtual environments.

And lastly, augmented reality can be achieved through non-visual content, such as haptics. In a CHI paper from 2017 [44] the authors devised a haptic system that allows the wearer of an HMD to actually feel the weight of a virtual object, but stimulating the user's muscles with electrical signals.

Chapter 3

Background

> "If one does not know to which port one is sailing, no wind is favorable"
>
> *Lucius Annaeus Seneca*

This chapter introduces significant concepts, terminology, and sailing scenarios that will be used in the subsequent chapters.

Before discussing the visualization system we have developed, it is imperative that we familiarize ourselves with the most important aspects about sailing. In the following chapters, I assume that the reader already knows the vital terminology.

First, I will explore the sailing context by looking at the anatomy of a sailboat and points of sail. Then, I will analyze the process of sailing a boat, in particular the feedback loop sailors use to maintain control of the boat under sail. Later, I identify three unique sailing scenarios in which sailors use different means to gather information regarding the status of the boat and its environment. I finish with a quick, comparative discussion regarding the processes sailors follow to obtain information.

Sailing is fun, there is no doubt about it; but one would be hard pressed to find an experienced sailor claiming that it is easy.

This chapter is not going to be a tutorial about sailing itself, but rather an evaluation of the devices, methods, and tools used in the process. The nautical terms I use can be found in any dictionary or beginner's manual on sailing; these terms, however, will be kept to a minimum.

Much like the process of controlling any device, sailing is a matter of observing what the boat is doing, processing the observed data (i.e. analyzing the data), reasoning, and performing actions (i.e. controlling the boat). The repetition of this sequence becomes the feedback loop that I will explore at length in the following sections.

Depending on the type of boat and the technology available on it, I will identify and explore a few different categories of options regarding information acquisition.

I will discuss the information acquisition process the captain goes through in three different scenarios. The term *cognitive load* is a loaded term; it has varying meanings in several fields of academic inquiry, among which one of the most significant being cognitive task load analysis as encountered as a branch of software design [45]. My understanding and limited use of terms such as cognitive load, cognitive effort, or cognitive strain can be seen as the sum of mental actions sailors need to perform in order to achieve a certain outcome. This includes actions such as remembering details, analysis and processing of data, synthesis of information, and the effort involved in planning and maintaining the oversight of physical activities.

However, I will use these terms informally, without appealing to any particular theory of cognitive processing. My approach is largely qualitative, as I examine the underlying interdependence among several factors.

The three identified categories mentioned above are:

1. Pure sailing or sailing unaided by any instruments other than the human senses (e.g. dinghy sailing);

2. Sailing aided by instruments, as well as the human senses (e.g. larger boats that may have an anemometer, depth sounder, a GPS chart-plotter, etc.);

3. Sailing aided by our proposed marine visualization system, instruments, as well as the human senses.

3.1 Sailing Context

In this section I will introduce the main sailing concepts that will play a role throughout this document, first by looking at the most important parts of a sailboat and then at the process of sailing itself.

3.1.1 Anatomy of a Sailboat

The distinctive difference between sailboats and other boats is that sailboats rely on sails for propulsion. In order to facilitate propulsion using sails, there are several unique hardware components that sailboats must have.

There is considerable diversity in sailboats, from the tall ships of old, with several masts to experimental kite-powered foiling hulls and many more in between. For the purpose of this chapter, however, I will focus on one of the most common sailboat layouts, the masthead sloop, featuring the following:

- ☐ A weighted keel;
- ☐ One mast;
- ☐ Standing rigging;
- ☐ Running rigging;
- ☐ Two sails - a head sail and a main sail;
- ☐ A steering system.

The keel serves two purposes: first, together with the rudder it prevents sailboats from sliding sideways and thus allows the force exerted on the sails to be transformed into forward propulsion. Second, a weighted keel balances the lateral force exerted on the sails, in order to prevent boats from capsizing. In the case of sailing dinghies (e.g. Laser dinghy), the keel is replaced by a centreboard or a dagger-board that serves the first purpose, however, leaving the sailor in charge of managing her position relative to the dinghy in order to balance it.

The mast is a spar that extends upwards from the deck of the boat and its purpose is to allow sailors to hoist, lower, and hold the sails up.

The standing rigging is a system of cables that hold the mast in place by connecting it to the hull.

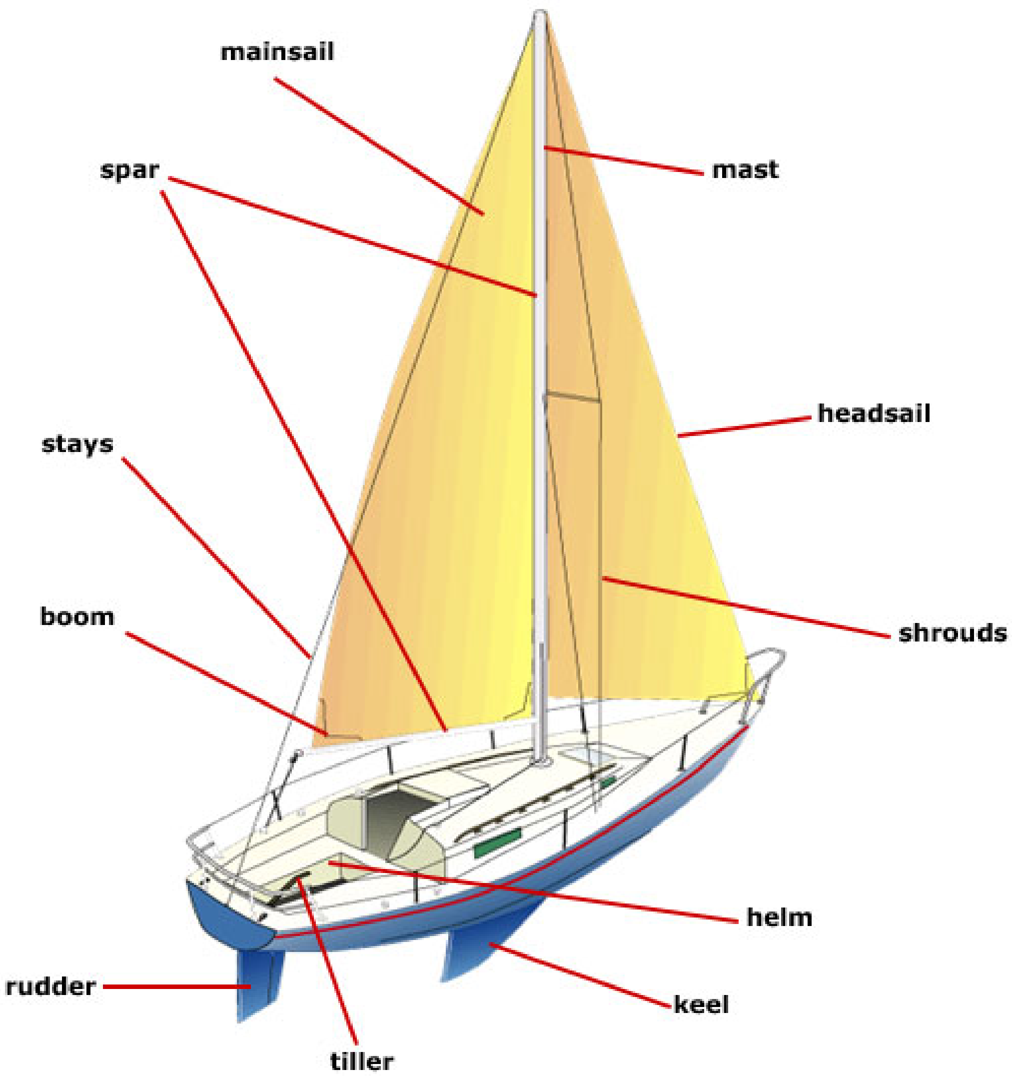


Figure 3.1: Sailboat Diagram

The running rigging is a system of ropes that allows for the movement of sails, both upward/downward and sideways, called halyards and sheets, respectively.

The sails are sheets of canvas, most often triangular in shape and typically made of Dacron material, that form an upward wing shape. The sails are used to harness the force of the wind.

The rudder steers the boat. It controls the turn rate of the boat. The rudder is controlled either by a tiller or a steering wheel.

3.1.2 Points of Sail

We have all seen floating objects drifting downwind, so, naturally, most beginners think that sailboats would travel downwind. With modern sail rigs it is possible to use a sail as a wing, and by using the lateral resistance of the keel, to transform the force generated on the sail into forward motion, even when traveling against the wind.

The different angles the boat intends to travel, relative to the wind direction, are called points of sail. The points of sail will influence many aspects of sailboat operations, for example sail adjustments (trim) or heel. When running (i.e. sailing downwind) the boat does not heel, but sailing close hauled (i.e. sailing closely into the wind) produces significant heeling.

3.2 Feedback Loop

The focus of this dissertation is not only to propose a marine visualization system as a digital aid to control a sailboat, but also to compare it to more traditional sailing methods that preceded it. For this purpose, I will first look at the common characteristics that most sailing methods share.

At its most basic, the process of sailing can be broken down to a loop with the following three steps:

1. Observation. The skipper observes the behaviour of:
   (a) The boat: heeling angle, sail trim, rudder angle, motion, etc.;
   (b) The environment: wind direction and strength, tidal currents, depth tendency, etc.
2. Reasoning. The skipper decides on a strategy for the next actions.

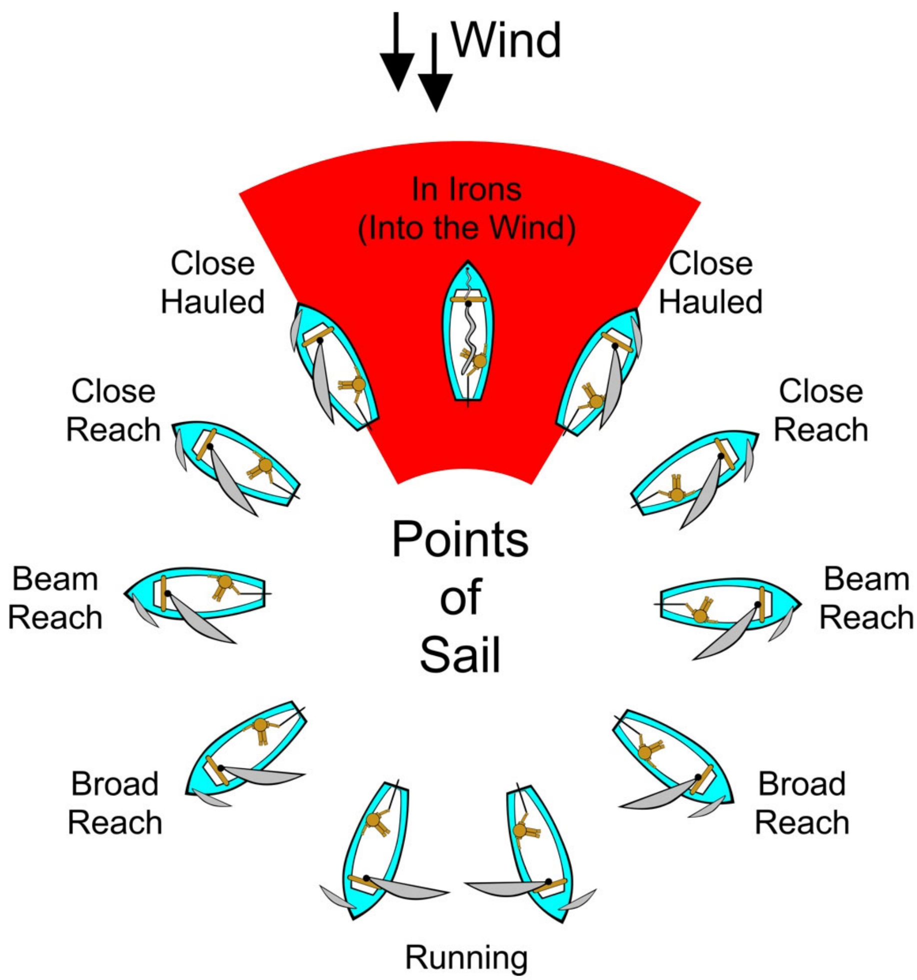


Figure 3.2: Points of sail

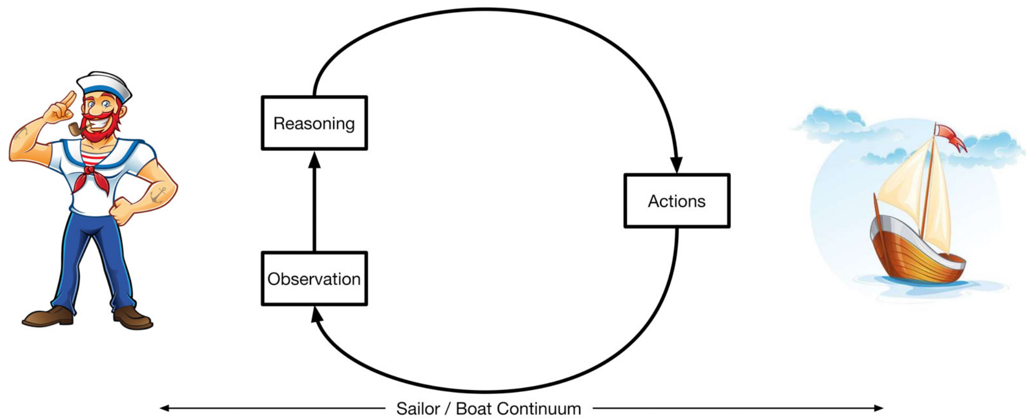


Figure 3.3: Operation Feedback Loop in the Sailor/Boat Continuum

3. Action. The crew/skipper performs actions according to the outlined strategy.

At every new iteration of the loop, the expected results are compared to the actual results and the error is taken into account in the reasoning step. In the next section I will further break down the steps and investigate the tasks that determine a higher or lower mental workload, depending on the technological aids used.

3.3 Sailing Scenarios

There are as many ways of sailing a boat as there are sailors, but for our purposes, I have identified three sailing scenarios: unaided by technology, aided by instruments, and aided by the marine visualization system.

All three methods follow the same basic feedback loop structure and achieve the same goal: safely sailing a boat. Once I go deeper and explore more details, I can identify both subtle and not-so-subtle differences that have significant consequences regarding the mental workload imposed onto the sailor.

In the diagrams used for the different scenarios, the various entities are organized relative to the horizontal and vertical axes, like in Fig. 3.4. On

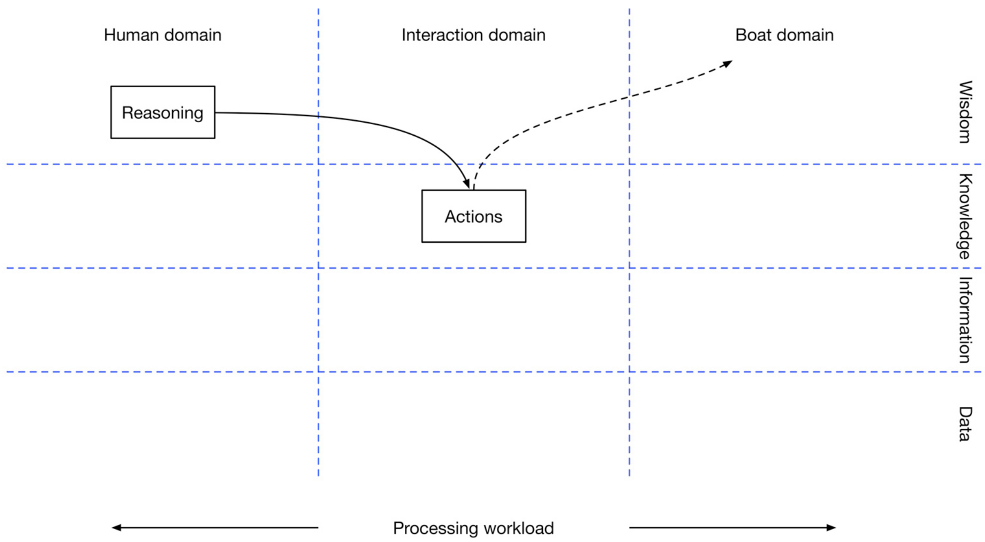


Figure 3.4: Axes

the horizontal axis I have identified three distinct domains:

- ☐ The human domain is where we place processes that require human effort without interacting with the boat (e.g. feeling the wind, analyzing the tidal current, reasoning, etc.);
- ☐ The boat domain is where we place processes that the boat facilitates (e.g. analyzing depth tendency, sensor readings, etc.);
- ☐ The interactive domain is where we place processes of interaction between the human and the boat (e.g. acquiring data from visualizers or instrument displays, actions such as steering, etc.).

On the vertical axis I use a simplified version of the DIKW hierarchy. The DIKW model tries to classify purported structural and/or functional relationships as data, information, knowledge, or wisdom.

"Typically, information is defined in terms of data, knowledge in terms of information, and wisdom in terms of knowledge." [46].

For our purpose, we broadly define these concepts using the following meaning:

- ☐ Data - raw, unprocessed quantitative evidence, representing various aspects; data requires significant mental filtering and processing to be considered useful in real-time;
- ☐ Information - quantitative and qualitative data that has been synthesized for a certain purpose; information is useful, due to its synthetic and focused nature;
- ☐ Knowledge - can be seen as meta-information, or ways to achieve something using information (i.e. know-how relative to a specific topic);
- ☐ Wisdom - strategy, reasoning, general know-how.

In the effort of trying to attempt to understand the factors that determine the process sailors go through to acquire information, I first look at the complexity, position on the diagram, and number of tasks that the skipper has to perform throughout the different scenarios.

3.3.1 Sailing without Instruments

In my first scenario, let's assume we are sailing on a boat that has no instruments whatsoever, not even a mechanical wind indicator. This is the ancient way of sailing; the Vikings sailed thousands of miles into the unknown using nothing but their senses.

Skippers would be able to estimate the wind direction and strength by feeling it on their faces. They could estimate the water depth either visually or by using a weight tied to a rope. Experienced sailors can *read* the waters and estimate the direction and strength of tidal currents. The old sea-dogs can predict the incoming storm by their aching knees and joints.

This kind of sailing is still practised on sailing dinghies, where is it impossible to install instruments due to the size restrictions of the boats.

One of the most obvious problems is that it takes a long time to learn how to interpret and predict the behaviour of various natural elements reliably. Another problem is that given the qualitative nature of the sensory data, it is very difficult to make accurate longer term predictions about position or movement. Thus it is not only difficult to lay out a long term strategy, but it would also require constant attention by processing several disconnected sources of data. For this particular case, skippers face substantial sensing and processing challenges.

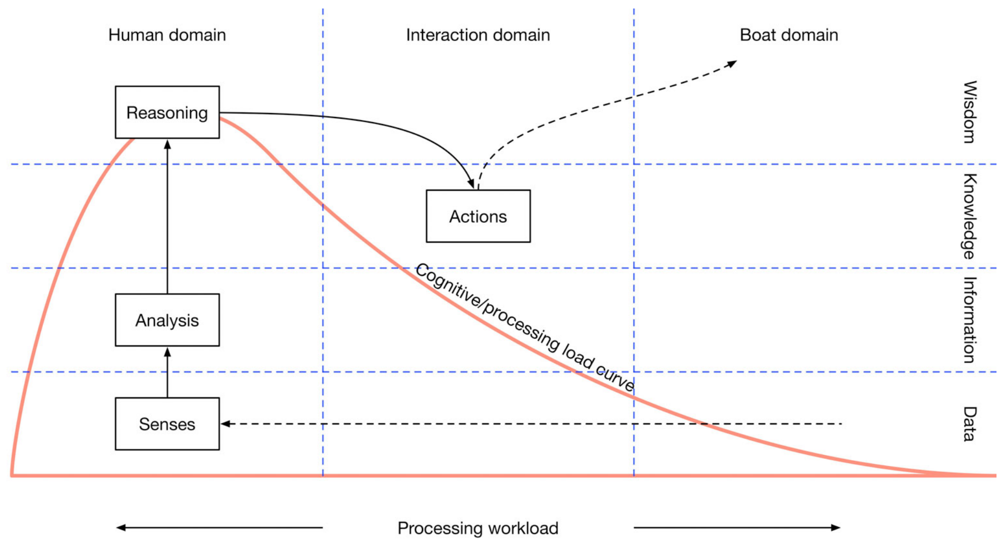


Figure 3.5: Sailing without Instruments

The process of sailing in this scenario is similar to the idealized feedback loop I introduced in section 3.2. The notable difference is that the observation step is broken down into sensory acquisition and analysis. For example, in order to determine one's movement over ground, we need to sequentially form two ranges and observe the movement of the foreground relative to the background. Then we analyze this data by triangulation. By incorporating it into a mental representation of the sailing scene, we can generate an estimation of the likely movement over ground and thereby the possible position at a given time in the future.

The horizontal axis in Fig. 3.5 represents a spectrum with the skipper on the left and the boat on the right. In the center, we see the actions where the skipper directly interacts with the boat. On the left we see the sensory acquisition, analysis, and reasoning, since all of these demand the skipper's attention and effort to perform. On the right we have nothing, because there is no useful information being collected by the boat. Everything the skipper knows, they know through their senses and mental processing efforts.

3.3.2 Sailing with Instruments

For our second scenario, I will assume a modern sailboat around 35 feet in length. This would be a common sight around the sailing community and many sailors would be familiar with the process of sailing such a vessel. In fact, most of the marine visualization system I discuss here has been deployed and tested on a Nicholson 35, a masthead sloop designed for blue-water cruising. These sailboats typically have instruments that aid in the process of data acquisition:

- ☐ Anemometer - an instrument that measures and displays information relating to the apparent wind direction and strength;
- ☐ Depth sounder - an instrument that measures and displays the water depth under the boat;
- ☐ Impeller log - an instrument that measures the speed of the boat relative to the water;
- ☐ GPS digital chart-plotter - an instrument that displays the boat's position relative to a digital marine chart.

For more detailed information about these kinds of instruments, please see section 5.2.3.

In this scenario, skippers rely on instrument readings for acquiring instant data regarding the wind, depth or speed over water, position relative to the ground, etc. Using the displays, skippers would constantly analyze the data, then incorporate this information into the process of reasoning according to some strategy. Afterwards, skippers would perform certain actions such as trimming the sails or steering a certain course.

The process of sailing in this scenario is still similar to the idealized feedback loop introduced in section 3.2. The main difference between this scenario and the first scenario (as seen in section 3.3.1) is that the data about both the environment and the boat is coming from instruments as opposed to the senses. That means that the instruments displace some of the sensing workload from skippers to their boats by filtering some of the raw data and presenting more focused data.

For example, in this scenario skippers can rely both on the GPS chart-plotter and on the depth sounder information to avoid collision with a reef or other underwater threats. Without these instruments, determining the risk

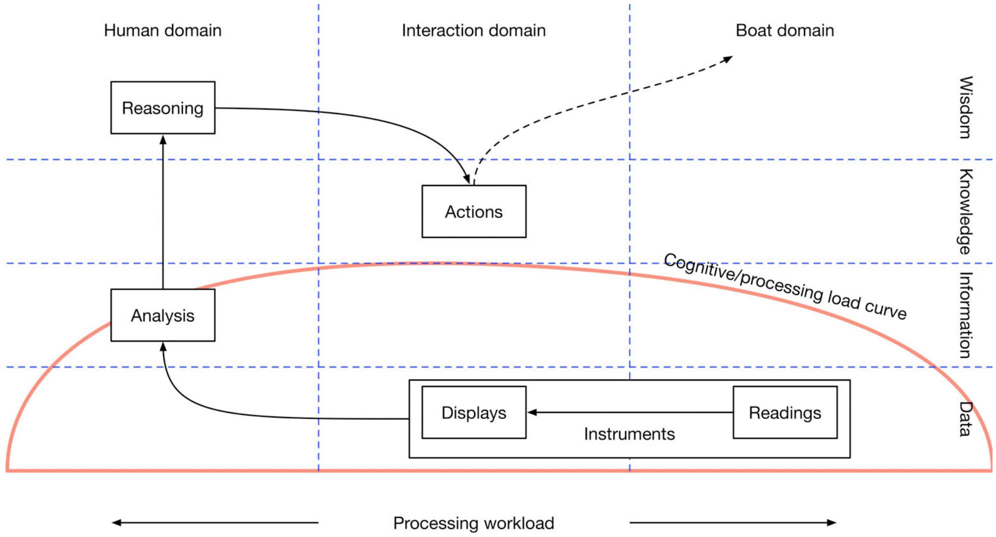


Figure 3.6: Sailing with Instruments

of such threats would be difficult and would most likely determine a different sailing strategy. In figure 3.6 we see a similar diagram to the previous scenario with the added difference that now the skipper gets the relevant data using the instrument displays. These, in turn, get their raw data from the adjacent sensors, which are integrated into the boat's systems. Skipper don't acquire data from the sensors directly, but rather through the displays, which filter the data to a certain extent, yet still require careful analysis.

The displays are positioned in the diagram in the centre and the sensors on the right side. Skippers have more accurate data that demands less mental processing, thus reducing the workload and freeing up time for other tasks.

3.3.3 Sailing with the Marine Visualization System

Our third and last scenario is that of the same boat from the second scenario, including the same instruments, but in addition to those, featuring the marine visualization system.

The marine visualization system can be deployed using two different modes:

- ☐ As an exocentric mode visualizer (e.g. a fixed tablet in front of the steering station, a regular screen in the cabin or potentially a VR HMD) where the orientation of the virtual content is determined by the boat's orientation relative to its environment; or

- As an egocentric mode visualizer (e.g. a mobile phone/tablet or an AR HMD) where the orientation of the virtual content can be controlled by the user's motion, relative to the boat's immediate environment.

Our visualization system does not discriminate between these two visualization modes. However, since I could not find any AR HMD that would be rugged enough to withstand the marine environment, I developed my solution using the exocentric mode only, for which I employed marine-grade ruggedised screens.

The virtual content the system displays is one of the main topics of this dissertation. Its most significant characteristics are:

- An interface in which various relevant scene entities are displayed relative to one another;
- Animated particle cloud-based natural visualizers for the wind, water current, and movement over water;
- A diorama-style abstract visualizer that represents synthesized information from a bird's eye view;
- Tendency panels for depth, barometric pressure, and others;
- A numeric panel with raw data from the sensor readings.

For an exhaustive list of the scene entities, please see Chapter 6.

In the previous scenario, skippers retrieve data from several scattered sources and then analyzes the data to derive the useful information needed in the reasoning step. Using the marine visualization system, however, skippers have access to already analyzed data that is displayed using visualizers which contain immediately useful information. For more details about the visualizers, please see sections 6.3.1 and 6.3.2. Skippers still have access to lower-level data in the form of either tendency graphs or numerical raw data, if needed.

The process of sailing in this scenario is similar to the previous scenario, but with a few significant differences (please see Fig. 3.7.).

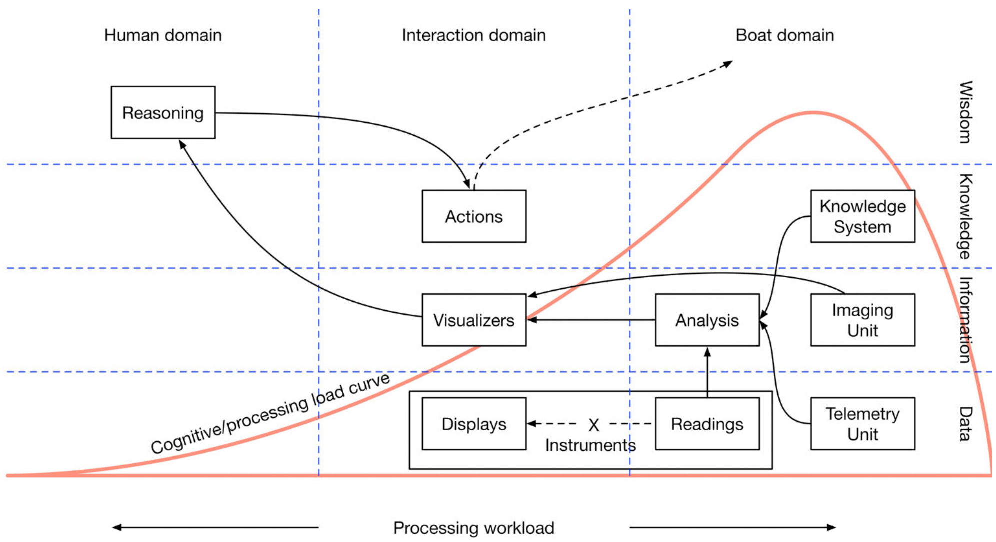


Figure 3.7: Sailing with the marine visualization system

First, because the marine visualization system uses only the instrument sensor data, the displays of the instruments become redundant, so they are eliminated from the feedback loop. Then, the analysis step is removed from the left side of the spectrum and placed on the right side, where the generated information is provided by the system using the visualizers. And last, users acquire immediately useful information from the marine visualization system via the visualizers, before going through the process of reasoning.

Using this paradigm, both the sensory acquisition as well as the analysis processes are moved to the right side of the spectrum, thus meeting the skippers' need for easily accessible information. In fact, we can see in the diagram that the process of observation has been reduced to simply immersing oneself into the marine visualization system, where most of the important information is readily available.

3.3.4 Comparative Scenario Discussion

At this point in my research it is important to differentiate fact from opinion or assumptions. The previous three sections described different ways of accessing content in an objective manner.

In this section, however, I explore a set of assumptions from an autobiographical perspective, drawing observations from personal use of the augmented reality system I built [47]. I am not trying to state immutable facts, but rather to explore potentially subjective matters that remain to be further explored in the subsequent chapters. This also means that this is based on my own experiences with sailing and with the development of the visualization system derived from a sequence of design iterations (see Chapter 4).

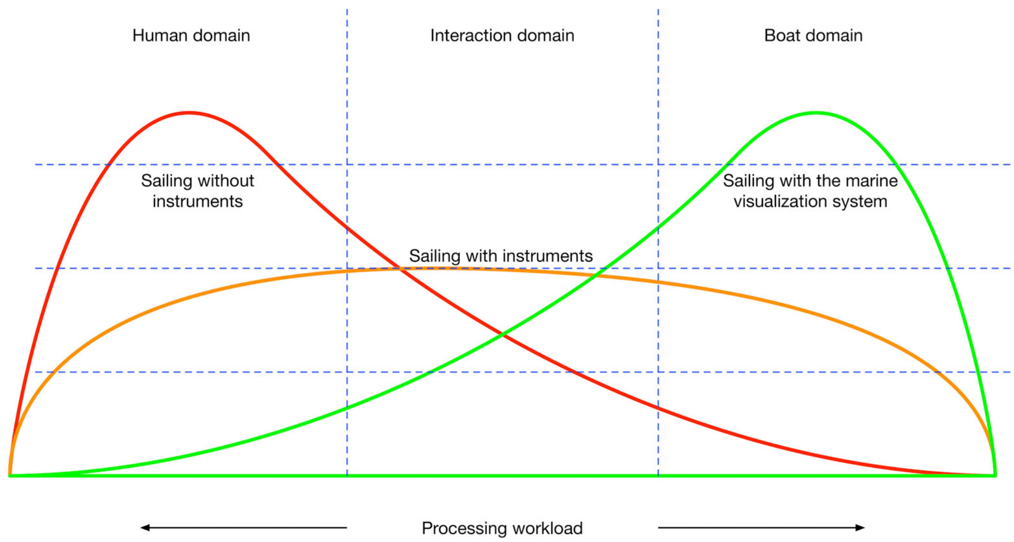


Figure 3.8: Processing workload comparison

In the first scenario, skippers have to acquire all the relevant data using their own senses, then analyze this data and use it for reasoning, all in real-time.

In the second scenario, skippers collect data using the instruments' displays, and then they must still analyze the data and make decisions based on it.

In the third scenario, skippers accesses information that has already been analyzed and synthesized by the boat, with a focus on providing instant, specific, immediately useful information.

I assume that the easier the observation process is (i.e. obtaining higher-quality, focused information), the lower the cognitive effort of the skipper. I also assume that by off-loading some of the processing effort from the human domain to the boat domain, I may reduce the cognitive strain. Figure 3.8

shows a comparison of the cognitive process between the different sailing scenarios.

3.4 Summary

In this chapter I presented vital information pertaining to the process of sailing a boat, including an introduction into the sailing context, control feedback loop, and a discussion of a few sailing scenarios.

In the first section, 3.1 I introduced terminology regarding a sailboat's anatomy (see 3.1.1) and points of sail (see 3.1.2).

In the next section, 3.2 I discussed the process of sailing a boat, by using and identifying the individual components of a feedback loop.

In the last section, 3.3 I identified and presented three sailing scenarios and followed up by engaging in a discussion of the scenarios when compared to one another (see 3.3.4). The three scenarios are sailing without instruments (see 3.3.1), sailing with instruments (see 3.3.2) and sailing with the marine visualization system (see 3.3.3).

Chapter 4

Preliminary Designs

> "Be thankful for problems. If they were less difficult, someone with less ability might have your job"
>
> *Jim Lovell*

In this chapter I follow the design process that resulted in the current direction of my research project.

In the previous chapter, 3, we looked at various aspects of the problem as we tried to answer the question *why are we researching this?* Here we embark on a journey to seek answers to another fundamental question, *what is the solution going to be?* And in Chapters 5, 6, and 7 we answer the question *how are we implementing the solution?* from three perspectives: hardware, visual content, and conceptual flow, respectively.

The difference between this chapter and Chapter 7 is that this chapter explores different ideas and directions in order to settle on a desired vision, while Chapter 7 explored the different kinds of content used to fulfill this vision.

As the title suggests, this chapter follows the design process by taking a close look at a detailed timeline that tracks the various iterations of the design process, from early concepts all the way to the current, final design.

I begin by attempting to identify the motivation that led me to pursue this research project. Then, in section 4.3 I look at the first idea for a general direction: a fully autonomous sailboat. In the next section, 4.4, I try a different approach, a semi-autonomous sailboat featuring a unified visual interface. And last, in section 4.5, I focus my scope to provide access to useful information using an AR environment.

Figure 4.1: SV Moonshadow in Hartley Bay, BC

Despite focusing our project on marine visualization now, this hasn't always been the main focus of my research. To better understand where I am now and how I discovered which characteristics mattered most, I will have a look at how I got here.

For this purpose, I will describe the initial context and then examine the chronological succession of events and design decisions.

4.0 Motivation

The first idea of starting a research project related to sailboats came to me in 2013 when I embarked on a six-month sailing trip to explore Canada's Pacific Coast (see Fig. 4.2 Map of the 2013 expedition). I had no experience whatsoever with sailing or anything related to the ocean and I had just bought SV Moonshadow, a 26' Paceship, only a few months before setting sail on the expedition. At that time I was at the beginning of my PhD and I was looking for research ideas.

Sailing is not an easy task, especially when sailing alone in some of the most remote areas of the Pacific Coast. In fact, sailing is one of the most complex examples of vehicular control. Even though things happen relatively slowly in sailboat operation compared to flying or even driving, the number of parameters involved in successful sailing is significantly higher. These include the weather, topography of the shore and seabed, wildlife, man-made structures, marine currents and many more. So, I decided to investigate the possibility of a technological approach to simplifying the sailing process, and thus potentially increasing safety and pleasure at sea.

4.1 Autobiographical Design

For our purposes, within the limited scope of this dissertation, my team chose to approach the testing of various elements of the system from an autobiographical perspective by following this method, based on [48]. I started with an ideation session, then established assumptions, tried implementing several ideas, and finally reached conclusions regarding the feasibility of the ideas by comparing the conclusions and the assumptions [49].

I decided early to pursue an autobiographical design as my research method to guide the design process, being influenced by similar research projects such as [50]. I experienced many iterations and failures before reaching stable solutions to sub-problems, a process well established, [51]. I built an extensive database of observations in the form of notes, logbooks, sound recordings, photos, and videos.

The autobiographical design method is a study or design testing method that involves the designer actually personally using the prototype during the design iterations, similar to [52]. The designer uses and evaluates the prototype himself, as opposed to competing methods of testing such as user

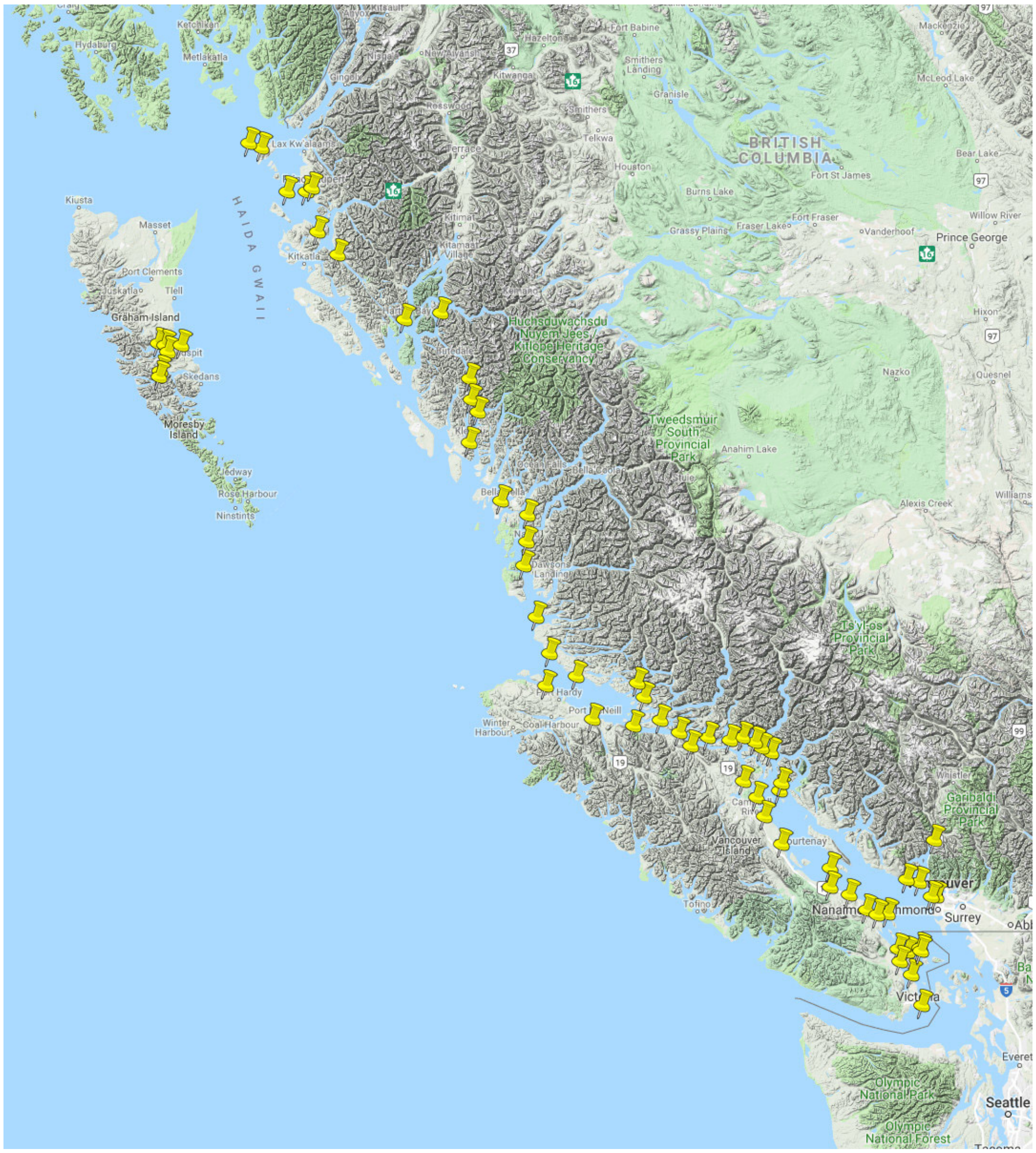


Figure 4.2: Map of the Northward Bound 2013 research expedition

studies, whereby users unfamiliar with the prototype are invited to evaluate it, [53].

Developing sailing applications is a good fit for autobiographical design when the researcher has access to a sailboat, because the prototype can be actively tested at each iteration, as in [51].

4.1.1 Alternatives

One good example of that was testing different constants for the PID system used to implement the autopilot. This process involved the mathematician who designed the model and me sailing for several hours, trying out different values and taking notes on the behaviour of the vessel.

An alternative design method is beta-testing, [54]. This calls for the prototype to be tested multiple times on a sample of likely customers. In this method, the researcher does not test the prototype directly; instead he collects observations from the beta-testers.

A second alternative is experimental design, where the designer creates a simulator to test the product, [55]. I employed this method in the first phase of the autopilot development efforts while ironing out details such as electronics, motor drivers, sensing devices, etc. I created an obstacle course and tested several iterations of the autopilot, until it successfully and repeatedly navigated through it.

4.1.2 Limitations

Some of the obvious limitations of autobiographical design are the expert knowledge of the user and blind spots regarding the experience of other users. The researchers are usually highly experienced and knowledgeable regarding the system, [48]. This expertise in their field can cause them to forget what a layman might be able to do with the product.

For example, Sam knows how to set up a solar panel and battery charging system, but Jimbo has no idea how to do it. The task might feel trivial to Sam, but it wouldn't be for most other users. This is a significant limitation when it comes to designing a product that targets many different kinds of users.

Our system, as a prototype, needs to work with a limited set of users in mind, at first; yet, eventually it has to have the ability to be extended to a broader user base. One of the hazards of using the autobiographical method is that the researcher can end up designing a product that is best suited for him and only him, [53].

4.2 Timeline

Fundamentally, sailboats have not changed in a very long time. Materials have improved, no doubt. But even the most modern, blue-water sailboats today have basically the same components as the lateen boats from the time of the Caesars.

If one of Professor Duncan's time-travelling adventures[1]would bring forward in time a viking warrior-sailor (please do!), he'd have trouble with many of our modern day contraptions, but skippering a modern sailboat wouldn't be a great difficulty. In fact, of all the vehicles people use today, the most familiar one to a time traveller from the past would be a boat, especially a sailboat. Operating a modern sailboat is almost exactly the same as it was in the time of the vikings, or even earlier, in the time of the Roman Empire: the boat harnesses the wind for propulsion using sails controlled by ropes and the boat is steered with a rudder.

This is largely due to the fact that no matter how many times people tried to improve sailboats, their original design was already quite efficient (see Chapter 3). Multi-hull designs and composite materials have certainly aided in optimizing certain aspects, but it's still sails and ropes all the way, thousands of years later.

Nevertheless, there is still considerable opportunity to apply technology to aid in sensing the immediate environment and perhaps even understanding it well enough to try out various degrees of automation.

4.2.1 Stage 1. Sailboat Automation (2013 - 2014)

This is where my research story really began: in April 2013, I weighed anchor and set sail, northward bound, trying to make it to Alaska aboard a small sailboat called Moonshadow.

For the first couple of months (section 4.3), I experimented with building an autopilot and interfacing the anemometer, but this proved to be too mechanically challenging to build while underway. Instead, I developed a

[1]Like any respectable history scholar should, Professor Duncan could time travel by making use of naturally occurring worm holes, often used for getting into trouble [56].

rudimentary network of electronic devices offering limited sensing capabilities, like motion (GPS, gyro) and orientation (accelerometer, magnetometer). Commercially available autopilots allow for user input using a rudimentary interface with a few buttons. Some advanced units allow for course input over a digital interface - e.g. Raymarine's Seatalk. In 2013, however, there were no commercial autopilot products that allowed low level access to controlling just the position of the rudder; that's why I decided to build one from scratch using a linear actuator.

After I returned to Victoria in September, I started working on a simulator for the development of the autopilot. I completed the job in December. It took a while, but the process was rewarding and when the autopilot became functional, it lived up to my design expectations. When the weather got better in March 2014, I started testing the autopilot in the open ocean.

Around the same time, I started working on debris detection, a vital component of the automation problem [39]. The other sensing capabilities, I experimented with also saw significant progress. Without a visual component to sense unpredictable obstacles on the water, however, the idea of full automation was untenable. It would be impractical to develop a fully automated device without a visual analysis component. Full automation means far more than following a given course; any functional autopilot can do that. I wanted a device that was able to steer clear of unknown obstacles; this would require a sophisticated visual information processor.

At first, the offline prediction proved promising, but it never materialized into a real-time solution.

This roadblock, around September 2014 became the first real crisis of the project.

After going back to the drawing board, I realized that I couldn't make the boat sail itself. Further, from an ethical perspective, I shouldn't even attempt it because I couldn't guarantee that my device would safely control the boat or prevent harm to others.

I could, however, make it easier for sailors to sail.

I took several months to consider what I had learned and forge a vision of what the realistic situation was, good and bad.

I pondered the nature of the difficulties sailors encounter and realized that there are simply too many disconnected sources of information. Sailors need access to readings from the anemometer, impeller log, GPS chart-plotter, and depth sounder, just to name a few of the instruments (see Section 5.2.1). In addition to reading these instruments, sailors also need to check the status of the sails, observe and read the currents on the water, be aware of wildlife and debris – all while planning ahead for the next course of action.

4.2.2 Stage 2. Data Sources (2014 - 2015)

Most of today's sailors have become experienced in sailing using instruments such as GPS chart plotters, depth-sounders, and anemometers. Without this technology, our Viking mates would do a much better job sailing our modern boat using ancient methods that call for a different kind of environmental awareness. They would rely heavily on reading the water and the wind, memorizing local landscapes, and maybe other techniques lost in the haze of history.

Recognizing the importance of being aware of the immediate environment started to point towards a new potential approach.

At this point in my research (early 2015), I realized that the integration of data from so many disparate sources of information about the environment placed a heavy burden on sailors.

The notion of developing a single, integrated representation of this disparate data became the focus of the second phase of my research (section 4.4), after I realized that full automation would be fruitless.

The visual paradigm shared by an overwhelming majority of the marine instruments available today is reminiscent of 1990s style displays, with their strengths and follies.

There is a reasonable explanation for the stagnation of this technology: the marine environment is harsh on everything, but especially on electronic devices. As such, building marine instruments takes a lot of development effort and usually implies testing against extremely demanding standards similar to those often seen in military applications specifications. Only large, well-funded companies can afford to bring products like these to market; this happens at a much slower pace than other types of electronic devices.

This turned out to be the first big crossroad where my approach veered away from the status quo. Instead of having several instruments, each with sensors and adjacent ruggedized displays, I would use the instruments' sensing capabilities, but discard their displays. Instead, I would use off-the-shelf display devices like tablets and smartphones connected to the boat's network to display a composite scene. I wanted to display all the data at one time in a way that was highly intuitive to interpret.

One obvious weakness is that non-rugged devices wouldn't last very long in a marine environment. A ruggedized smartphone, however, is considerably cheaper than rugged instrument displays. It also requires only one screen to display data from any number of instruments.

This decentralized, non-monolithic hardware approach also meant having access to all of the data on one display. Another major advantage is that by making the data transfer wireless and incorporating redundant processing units, a potential failure of any of the system components would be elegant (i.e. failing one a time), rather than catastrophic (i.e. failing all at once).

From a visual perspective, I was still at the beginning of my research. I experimented with numeric and 2D data approaches to displaying the data, but only achieved a virtual copy of the actual instrument displays. This meant that instead of physically having to switch between media for data, now we had to use the interface to virtually cycle through each data source.

Since the tablets I used were quite powerful, I realized I could adopt a Virtual Reality paradigm to render the data in a 3D virtual environment. By September 2015, I started experimenting with a few VR options suitable for tablet visualization.

4.2.3 Stage 3. 3D Content (2015)

Using virtual reality content meant that I could integrate all of the data into one 3D view. This proved to be another major crossroad in my project and I started focusing on rendering 3D content instead of just displaying the data.

My VR scene, at this point, featured an abundance of data, using colour-coded content in the form of animations. I experimented with particle clouds and vector representations. As one might expect, the scene prototype was cluttered with data; making sense of the various environmental components was difficult. In fact, during an informal conversation over a pint with an experienced sailor, my drinking buddy argued that it's simply easier to read the boat displays instead of the busy VR scene.

4.2.4 Stage 4. Augmented Reality (2015 - 2018)

By early October 2015, I had collected enough unfavourable opinions on the interface appearance and functionality to feel the pressure to choose a different direction. As I explored different ideas and options, I learned that if I integrated either the cameras of the handheld devices or a bow-mounted camera, then I could make the jump to a genuine Augmented Reality paradigm. By using Augmented Reality, I would greatly enhance the sailors' environmental awareness because the virtual content would be registered in real space by synchronizing it with the video-feed from the camera which would provide the background.

Here I hit another fork in the road: I had to choose the focal point of my AR scene. If I use the camera feed from the tablet, then the virtual content would be rendered according to the perspective of the tablet. If, on the other hand, I used a video feed from a bow mounted camera, the content would be conceptually related to the boat's perspective, in particular, to the perspective from the bow of the sailboat.

There are advantages and disadvantages to both approaches, but ultimately I looked at sensor data accuracy. An average tablet weighs 1lb and a typical sailboat weighs 20,000lb. The accuracy of the motion and orientation (e.g. accelerometer, gyro and magnetometer) sensors used on both the tablet and the boat are comparable; the mass is of the device the sensor is strapped to is important.

The sensor readings regarding the boat's orientation were considerably more reliable. This translated into much better synchronization between the real and virtual content of the visualization, so I chose the boat-centred approach featuring a bow-mounted camera. In late 2015 I published a journal paper at the Cyberworlds conference that provided several details about the state of my research at that point.

By mid 2016, having completed most of the important mechanical, electronic, networking, and processing aspects, I could now turn my attention to optimizing the virtual scene.

Realizing that I was heading towards the conceptual aspects of organizing the content, I started an inquiry into the various theoretical frameworks I could use to structure the underlying essence of the visual content, such as ontology and mereotopology.

It was obvious that I needed a system to represent the nature of the content, but the geometric-focused approach did not yield any promising results, perhaps with the exception of ontology, which produced an experimental hierarchical description of the content. I realized that the discussion about the content is not only about the visual appearance itself, but also about the meaning of the parts of the visual scene.

I thought I hit a dead end because the AR content would only be a direct visual representation of the data. I employed a few techniques that improved the visual feel of the AR scene, in particular the particle animations, but I also knew something major was missing.

4.2.5 Stage 5. Conceptually-Modelled Content (2018 - 2020)

Neither the geometric-focused, nor the mereology approaches provided the underlying foundation I was looking for, so I realized that I needed to change the framework of my investigation to address aspects like perception and abstraction to examine the meaning of the scene content. This, ultimately, determines the structure and appearance of the scene entities. By October 2018, I realized that it was time to reach out to experts in the field of philosophy of mind and philosophy of science; this proved to be a fertile and auspicious endeavour.

From a series of papers from the field of philosophy of science, I noticed a common pattern regarding the usefulness of accuracy versus abstraction in information modelling. I realized that improving the accuracy of the model did not make it easier to understand. At the other extreme, a model that is too abstract is also undesirable. So, scientific models have to be accurate enough to deliver their information content, but abstract enough that the information does not become overwhelming.

This one idea triggered a dramatic paradigm shift in my understanding of the value of the content in the context of my research. It also inspired me to not be bound by the rigours of a direct visual representation, but rather to stay true to the purpose of a visual interface which would provide useful information. That meant that as long as I aimed at increasing awareness about the environment anything goes from a visual and conceptual perspective.

Investigating the visual content of the scene suddenly became a problem of modelling the conceptual meaning rather than the graphical appearance of the virtual content. By March 2019, I looked closely at how to gather clues regarding the meaning of both the sensory information collected as well as the sailors' needs and limitations in assimilating this information.

I used the Data-Information-Knowledge-Wisdom hierarchy tool (see 3.3) because it allowed me to model the sailing process in terms of levels of abstraction of information relative to specific tasks. According to this hierarchy, the main difference between data and information is that data is objective and it serves only to quantify something. Information, on the other hand, incorporates not only the underlying data, but also a qualitative description of the observed entity and its context (meaning, use, relationships, etc.).

After a long process of conceptual analysis and synthesis, I managed to identify a series of insights, design and conceptual principles, and ultimately features which served as the basis of the development of new kinds of visual content.

Among the concepts I found to be most valuable were those of pseudo-natural appearance, distorted content, and conceptually metamorphic content.

Pseudo-natural appearance applies to content that looks and acts like its real-life counterpart regarding most of the observable characteristics. There is, however, one very obvious and easily recognizable difference that gives users a clear idea that the content is virtual, not real. Using pseudo-natural content conveys visual information that will be displayed in the interface as close as possible to real information, despite it coming from a source that normally doesn't have a visual representation.

A way to achieve pseudo-natural appearance is by employing distorted content. This kind of content is conceptually modelled to change the underlying meaning of the content which, in turn, changes the appearance of the content. I have identified several ways to conceptually distort content.

For example, I could combine the idea of a flat plane of movement (along the surface of the water that spans from the boat to the horizon) with the idea of a gravity well. The visual and conceptual content of a gravity well makes the viewer assume unseen forces, such as the force of gravity.

When we combine the fact that the surface of the water is planar with the perception of the gravity well pulling one towards its centre, then we can visually distort the planar image to make users feel as though they are drawn towards the centre. This means I can use this visually homogeneous graphical representation as an example of a conceptually composite entity which can illustrate in a visceral manner the direction in which the boat is moving.

By comparison, an abstract representation of the boat's motion could be something like a 3D vector arrow, which would require cognitive processing to understand the direction of motion, as opposed to simply feeling being drawn along the direction of motion through a cunningly warped spatial representation of the background image.

Normally, visualization research project have a user-study of the content that is being proposed; I certainly agree that it would be highly beneficial to have such an empiric evaluation. Given the broad scope of the problem I was addressing and the equally vast solution, including significant hardware, software, and conceptual components, I had to consider evaluating the content from an autobiographical perspective, by carefully tracking observations, while moving through several design iterations.

4.3 Phase 1. Sailboat Automation

The idea of making sailing more accessible is clear and easy enough to understand, but to actually turn this idea into a research project, I collected facts and observations along with surveys of existing technology and its limitations. My first insights emerged by considering a set of design principles. This led me to a new problem statement.

Using these initial insights and design principles, the first problem statement started to become a bit clearer to me and I started working on the first design challenge.

4.3.1 Problem 1.0: Sailing is Difficult

Initially, we came up with the following problem statement:

- ☐ **Who:** Sailors, young and old, experienced and inexperienced
- ☐ **What:** Sailing to be made trivial
- ☐ **Why:** Sailing is too difficult - it requires lots of practice to master and significant physical and mental stamina
- ☐ **Where:** Inland, coastal and offshore waters
- ☐ **When:** At any time, but especially in rough weather conditions

So, we asked ourselves:

Design Challenge 1.0: *How might we* design some kind of technology that will make the sailing process trivial?

4.3.2 Solution 1.0: Autonomous Sailboat System

Jumping to the first daring idea was easy: design an autonomous system that sails the boat. This meant I could transfer the knowledge needed for sailing to an autopilot system, instead of training every single skipper. The sails would be automatically controlled with electric or hydraulic systems.

Pros:

- ☐ Easy to use by anybody
- ☐ Requires very minimal input from the skipper
- ☐ Requires no physical interaction with the sails/anchor
- ☐ The data collected from the sensors and used by the system can be visualized, as an added bonus

Cons:

- ☐ Prohibitively expensive hardware (electrical/hydraulic components)
- ☐ The system complexity would be so high it would require financial means beyond academic funding limits
- ☐ Existing boats cannot be easily retrofitted

It became obvious soon that I simply did not have the resources for such an endeavour and that even if it worked, it would not be feasible for widespread use due to the high hardware costs. Another issue is that it would remove the hands-on aspect of sailing to such an extent that it would take the fun out of sailing altogether.

4.4 Phase 2. Semi-Autonomous Sailboat System

As the need for another iteration of the design process became obvious, I tweaked and re-examined the insights and design principles to find clues on how how pose a problem statement with more realistic potential solutions.

4.4.1 Problem 2.0: Sailing is Complex

- ☐ **Who:** Sailors and crew
- ☐ **What:** Sailing to be simpler

☐ **Why:** Sailing is too complex

☐ **Where:** Inland, coastal and offshore waters

☐ **When:** At any time, but especially in rough weather conditions

So, once again, I asked myself:

Design Challenge 2.0: *How might I* design some kind of technology that would make the sailing process more accessible?

4.4.2 Solution 2.0: Semi-Autonomous Sailboat

Figure 4.3: On-route to Alaska, developing the first version of the network and processing server

For my first realistic solution, I proposed a system that used existing boat instruments as well as several devices that form a semi-autonomous sailboat control system. This system would control the boat's rudder, but nothing else. The sails would be manually controlled by the crew, while the skipper performed navigation tasks using contemporary methods (i.e. using a chart-plotter, depth sounder, etc.).

I realized I needed to design and build several system components to control the steering, detect debris, and manage the autopilot. An augmented reality interface would also provide the skipper data visualization.

Pros:

- ☐ Simplifies the sailing process
- ☐ Only requires temporary oversight from the skipper, as opposed to permanent attendance
- ☐ Existing boats can be retrofitted without great effort
- ☐ The data collected from the sensors and used by the system can be visualized

Cons:

- ☐ Requires installing a rudder control mechanism, a gimbaled camera on the bow, and a processing server which interfaces the boat's instruments
- ☐ The system complexity is significant
- ☐ Requires reliable debris detection (using computer vision methods), for safe operation

4.4.3 Prototype 2.0: Sailboat Control System

In accordance with the Solution 2.0 concept, I developed Prototype 2.0 consisting of a mechanical/electronic/software system (Figure 4.3) that takes in data from sensors, processes it, controls the rudder, performs debris detection and ultimately displays relevant information on a screen using an immersive AR interface.

Autopilot Simulator

One of the first intermediary steps to achieving my ultimate goal was to build a physical simulator which enabled me to develop and test the autopilot hardware and algorithms. This step allowed me to test the electronic components, such as the magnetometer, gyro, and micro-controller without leaving the lab.

I considered several control systems and ultimately chose a PID controller. I could not use GPS data in the lab (GPS does not work indoors), so I determined the heading and motion by the magnetometer and gyro, while the heal of the boat was derived from the accelerometer.

As soon as the electronic components were sufficiently reliable, I dismantled the simulator and reused the parts for the actual mechanical autopilot, in particular the linear actuator, which became the main mechanical actuator of the autopilot.

Rudder Control Unit (Autopilot)

The rudder control unit is a hardware component built around a linear actuator that performs the task of controlling the position of the rudder, and thus the direction of the boat.

This unit is controlled by the processing unit to determine the current rudder position and to alter the course of the boat. Seen from the perspective of a black-box paradigm, the inputs of the system are either the magnetic heading, GPS heading, or wind direction; the output is a transition to a specified position of the linear actuator.

Due to the mechanical constraints of the linear actuator (DC motor powering a worm gear), the electric controller reads the current position of the rod and powers the DC motor to reach the set position. I could not reliably achieve a desired rod position by using a constant motor speed, so I had to develop a method that slows down the motor proportionally to the distance of the target position.

As soon as I could accurately control the position of the rod, I devised a cunning PID strategy based on the GPS heading.

After many attempts at tweaking the PID system, I found the following value to best suit our needs:

- ☐ Kp = 20
- ☐ Ki = 2
- ☐ Kd = 1.2

The performance of the complete autopilot was outstanding, outperforming any commercial competitor, especially in rough weather[2].

[2]There was one interesting behaviour we had to learn to live with; on boot-up, the autopilot had a devious tendency to sharply turn toward the nearest reef or boat, terrifying the crew, missing the looming threat by inches, before running reliably, elegantly and

(a) (b)

Figure 4.4: Autopilot simulator: (a) side view, (b) top view

Figure 4.5: Autopilot in action

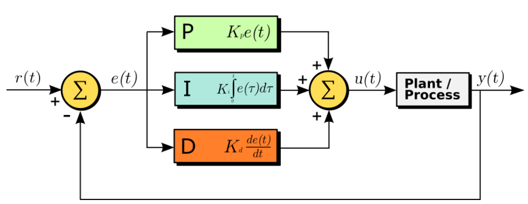


Figure 4.6: PID Feeback loop diagram

Processing Unit

The processing unit is a boat server that provides a number of built-in sensors (accelerometer, gyro, etc.), in addition to interfacing the boat's existing instruments. This unit is used mainly to perform the necessary computations

Figure 4.7: The Dangler

for the PID control of the rudder. It also serves as a computing platform for the debris detection unit. One final feature is the implementation of a WiFi network on which sensor and instrument data is broadcast.

Debris Detection Unit

This debris detection unit consist of two components: an early warning collision unit (aka *The Dangler*) on the bow and a computer vision program

smoothly for the rest of the trip. It took us about a year of putting up with this funky behaviour before discovering that there was a bug in the programming, where the integral sum was only properly initialized upon a change of course, and therefore starting at random values at boot-up. After I fixed the bug, the autopilot operation became less exciting, but certainly more relaxing and trustworthy, especially for the faint of heart running on the Processing Unit. The main goal of this unit is to determine whether there are any hazardous debris in front of the boat floating on the surface of the water.

Together with Tanmana Sadhu and under the supervision of A. Branzan-Albu, I launched my research on the debris detector in 2015. The off-line results were quite promising. I published the results of this research in 2016 at the Conference on Computer and Robot Vision (CRV). [39] Unfortunately, I shelved the project because it never achieved satisfactory results in real-world situations.

As for the image acquisition system, aka the dangler, while it did work well in normal conditions, in heavy seas it dangled too much. In later iterations, I attempted to reduce the dangling by enlarging the length and width of the dangler arm, but to no avail. I also experimented with a stabilizer, but that, in turn, introduced too much video noise. Nothing seemed to stop the dangling, so we ultimately abandoned the dangler altogether and decided to use a fixed camera for the next iteration.

I presented the initial results of the debris detection project at the Cyberworlds 2015 Conference and published them as a journal paper in 2016. [38]

Visualization Unit

The visualization unit is the graphics component of the system. Built upon an augmented reality paradigm, it aids the skipper in visualizing information collected from the sensors.

At this early stage of the project, the aim of the visualization was largely to cover the most important aspects (i.e. wind, current and movement over water) using particle systems as well as some other panels. For an in-depth analysis of the visualization component as of 2015, please see the paper "Augmented Reality Visualization for Sailboats" [38](Figure 4.8).

This was the first iteration of the visualization system our current research is focusing on. While it looked similar, there were key differences, mostly due to the fact that at the time we simply wanted to add as much information as possible, without much focus on what that information looks like or how useful it is.

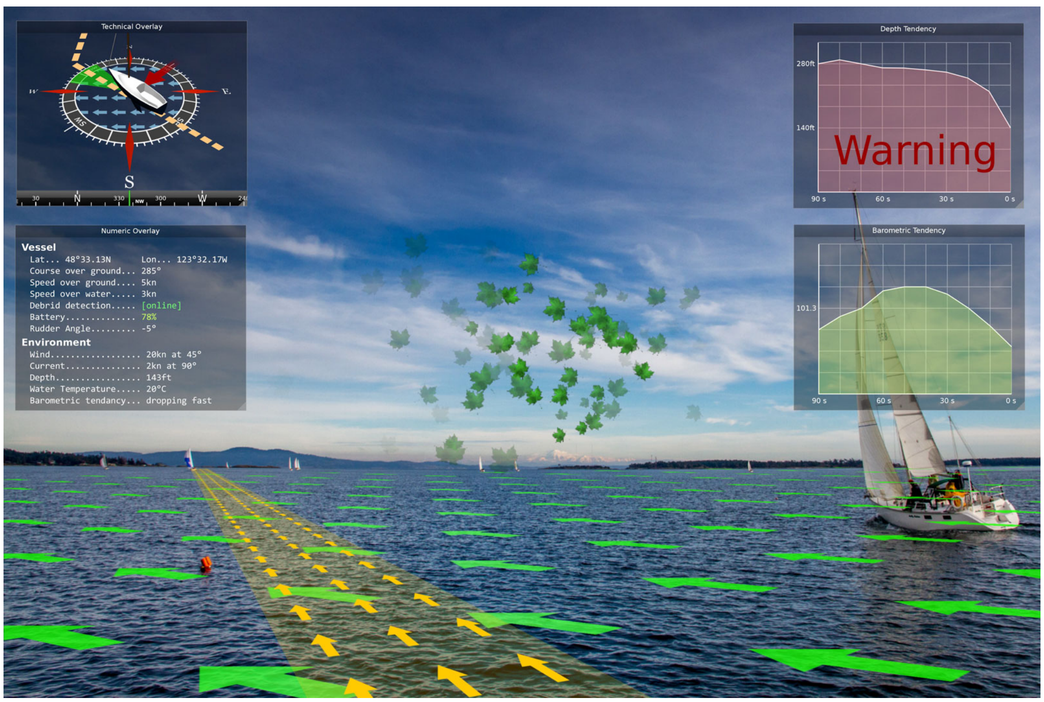


Figure 4.8: Early visualization concept

4.4.4 Solution 2.0 Observations

After publishing the two papers on the research project and after having the system partially operational for several months at sea, I gathered invaluable observations about the various system components.

- ☐ PID System Observations
  - Hard to get the right initial PID values
  - Reliable and good performance after 1-2 minutes of operation
  - Comparable performance with existing autopilot products (e.g. Raymarine ST6000)
  - Required tweaking for different sea conditions
- ☐ Rudder Control Observations
  - The linear actuator out-performed autopilot products, especially in rough sea conditions
  - Redundant and cumbersome if the boat is equipped with an existing autopilot
  - Ended up being used mainly as a way to determine the rudder position for the visualizer
  - Flexible solution and very cheap to implement if there is no off-the-shelf autopilot present
- ☐ Debris Detection Unit Observations
  - Only worked offline (i.e. on recorded data, not in real-time)
  - The results were satisfying and promising, but not stellar and not good enough to ensure safe navigation
  - Proved difficult to use the same algorithms in real-time
- ☐ Processing Unit Observations
  - The Arduino Mega ADK implementation though temporary, proved highly reliable and powerful enough for the test at hand
  - At this stage, the deployed unit interfaced instruments and sensors, and logged and relayed data

  - For debris detection, it would have been necessary to use much more powerful hardware (at least RaspberryPI)

- ☐ Image Capture System Observations
  - The gimbaled camera system dangled too much, especially in rough seas
  - The stabilized version introduced too much noise into the video feed

- ☐ Visualization Interface Observations (recorded from an autobiographical perspective)
  - Introduced many new visual elements, especially the immersive components using particle animations
  - The interface proved to be too busy and confusing at times
  - Too colourful and distracting at times
  - Colour coding for various elements should be replaced with shape coding if possible
  - Implemented in Qt + C++ and could not easily be ported to mobile devices

These observations were invaluable in continuing to the last phase of our research project, the marine visualization system.

After compiling the set of observations regarding the solution proposed in Phase 2, we realized that several components of the Sailboat Control System using the existing technology may be a dead end. In particular, the mixed results of the Debris Detector meant that the boat could not be trusted to stay on autopilot, requiring the crew to monitor the seas ahead of the boat at all times. The mechanical rudder control system also proved to become redundant if an existing commercial autopilot was installed. The image capture system was unsatisfactory and needed a major revision. In time, it became obvious that the visualization unit has several advantages that could be explored and expanded.

4.5 Phase 3. Marine Visualization System

The *marine visualization system* is the target of the current phase of development for our research. In this phase we focused on designing a system to aid in providing sailors with easy access to information regarding the boat and its immediate environment.

In this third and last major iteration of the design process, we revisited all the observations learned from the previous experiments and tried to figure out which aspects could be solved with existing technology (e.g. autopilot, commercial stabilized gimbaled camera) and which aspects were unsolvable with current technology and methods (e.g. debris detection).

4.5.1 Problem 3.0: Scattered Data Sources in Sailing

Sailors depend on a wide range of sources of data and most of these are scattered throughout the boat.

As an example, consider navigating a stretch of water that has tidal currents. First we need to find the tide tables and a clock and look up the particular tides levels. Then we get a chart book, where – based on the tide levels – we have an idea about the tidal current direction. Finally, we get the paper charts (or chartplotter) and plot a course that takes advantage of the best currents.

Other instruments include depth sounders, radar, and AIS, all of which are important, individual sources that demand the skipper's attention.

- ☐ **Who:** The helmsman
- ☐ **What:** Access to data from one centralized source
- ☐ **Why:** The data sources are scattered

So, once again, I asked myself:

Design Challenge 3.0: *How might I* design a system that will provide easy access to centralized data?

4.5.2 Solution 3.0: A Centralized Interface

After analyzing the results of the previous research projects, I realized that by discarding the unsuccessful/obsolete units (e.g. debris detection, autopilot etc.) I could still reuse most of the system components. So, I decided that I could contribute most by providing a centralized data system. This system would read the existing boat instruments as well as add several sensors, grouped as a telemetry unit, to provide users with access to data in one unified interface. The system would provide the helmsman significantly easier access to data.

It is true that several instruments can be centralized using modern technologies, such as NMEA2000 and displayed using chart-plotter units or chart-plotter software such as OpenCPN. These tools, however, display the information in very rudimentary ways, usually either numerically or using various kinds of simple 2D graphical representations. Several other data sources are usually unavailable on most sailboats (accelerometer, gyro, magnetometer, bow-mounted camera etc.) and our system incorporates all of these and more.

After examining our experience with Prototype 2.0, we soon realized how much of the previous technology we could use and that most of our subsequent focus should go into the visualization component.

This was the point when we decided it was time to go back to the drawing board and use all of the tools available in order to design an intuitive, innovative and, most importantly, effective visualization interface.

4.5.3 Problem 3.1 - Sailing Requires Access to Information

- ☐ **Who:** The captain
- ☐ **What:** Access to immediately useful information
- ☐ **Why:** The data sources are scattered and processing data into information is a significant mental effort

In the context of pure sailing, sailors on small sailboats learn to gauge things like current and wind speed through all kinds of intuitive visual and bodily cues (e.g. the feel of the swaying of the boat, visual cues from the appearance or movement of the waves, etc.)

There are, however all kinds of information that may be relevant to the sailor which are not intuitively available in this way (e.g. obstructions under the water, potential shifts in atmospheric conditions, subtle changes in wind direction, etc.)

Sailors working on larger sailing vessels are less able to navigate by feel in the same way, but compensate by using various kinds of instruments which can display things like wind speed, air pressure, current direction, etc.

The problem is that each of these readouts in isolation can be misleading. Looking at air pressure by itself, or current direction by itself, or wind speed by itself, ignores the ways in which these features interact in unforeseen ways. In order to sail effectively, sailors must be able to calculate the complex causal interplay between these features and how each feeds into the others. Having the information displayed on readouts in this way can be unintuitive, difficult to keep track of, and cognitively taxing on sailors who must attempt to integrate them.

Design Challenge 3.1: *How might we* design a system that will provide access to immediately useful information?

4.5.4 Solution 3.1 - AR Interface

We propose creating a system that integrates all this information for sailors and displays the information all at once.

This, however does not solve the problem of facing a significant processing effort. Now, sailors are inundated with all kinds of data, but are not provided with an intuitive sense of how to pull out relevant information from the data needed for effective sailboat navigation. There is so much information at once, that it becomes noise. We need some way to present this information that is intuitive and easy to digest, allowing for a response requiring minimal additional processing of the data.

One effective way to do this is to simplify the information provided by the visualizer. I can provide overly simplistic, abstracted, or idealized, representations to sailors to avoid information overload. This addresses issues related to cognitive processing, but it introduces a new set of problems: if I simplify or idealize the information I present to sailors, then the sailors are no longer acting on accurate information. Instead of correct information about their environment, they now have overly simplified accounts. Easier to understand, but far more dangerous, if sailors confuse the idealizing and simplifying assumptions for real facts about the world.

Bad choices can suddenly lead to disaster. The visualization cannot compromise with respect to accuracy, but in order to present the information in a more intuitive fashion, certain distortions or idealizations may be employed.

It appears I must make a trade-off between models being understandable and being accurate.

Therefore, in order to balance all of these concerns, I need a vehicle that conveys many different kinds of information to sailors in a way that is more intuitive than just a collection of different numerical readouts, but which also provides a greater variety of information than can be gained from pure sailing.

Lastly, I also need to ensure that the more accurate (but less intuitive) numerical information is still available to sailors in case the more intuitive representation is insufficient for their needs.

4.5.5 Prototype 3.1 - AR Visualization System

Once I had a vision of the big picture in my mind, I started adding detail to the picture. It was a long path, but I finally arrived at the heart of my research quest. Prototype 3.1 is the focus of this dissertation.

Our proposed marine visualization system is a composite structure comprised of various elements:

- ☐ Chapter 5. A hardware system that aggregates several mechanical, chemical, electrical, and electronic devices.
- ☐ Chapter 6. A software system that provides methods for interfacing sensors, processing data, transferring data across devices, and ultimately implementing an augmented reality interface.
- ☐ Chapter 7. A design-mapping system that manages the collection of insights, the emergence of conceptual and design principles, and ultimately the specification of features to be implemented.

4.6 Conclusion

I could not have made it here without testing the feasibility of certain ideas and ultimately keeping only those that worked in the long run. By testing, I don't mean user-testing as commonly found in HCI-related research, but rather testing the practical feasibility of various entities from an autobiographical perspective and recording the observations that emerged from the experiments.

I inherited the general idea of making the process of sailing more accessible from Phase 1, though the problem/solution of this phase proved not to be feasible due to obvious financial constraints.

I inherited the idea of using electro-mechanical automation wherever possible from Phase 2, but most importantly devising new technological contraptions to better support the overwhelming need to interpret the environment, in the form of providing visual aids.

Phase 3 represented a departure from the physical aspects of sailing and a focus towards providing more access to data regarding the boat and its immediate environment.

Prototype 3.1 inherits the need for data acquisition and visualization from Solution 3.0, and supplies added consideration toward a classification between data and information with the latter being immediately useful, and not requiring numeric processing as the former does.

Chapter 5

System

> "We must free ourselves of the hope that the sea will ever rest. We must learn to sail in high winds"
>
> *Aristotle Onassis*

In the current chapter I will create a detailed recount of most of the hardware and software elements that make up the system. The following chapter, 6, will explore the visual elements that make up the AR scene.

The system is comprised of a vast scope of elements, all working together. These elements are grouped into modules, based on the purpose they serve.

The sensing module (see 5.2) features the system's sensory capabilities, by interfacing various instruments and sensors. The module is divided into four units: the telemetry unit (see 5.2.1), the imaging unit (see 5.2.2), the internal unit (see 5.2.4), and the instruments unit (see 5.2.3).

The networking module (see 5.3) features the system's communication capabilities; it implements various networking solutions.

The processing module (see 5.4) features the system's computational capabilities; it processes acquired data and generating desired information.

Finally, the visualization module (see 5.5) features a brief introduction into the visualization capabilities of the system.

5.1 Overview

My approach to the problem of providing sailors with access to marine related information for vehicular awareness purposes is to implement a system that relies on sensory, processing, and visualization capabilities. The system is comprised of four modules:

1. Sensing Module;
2. Networking Module;
3. Processing Module;
4. Visualization Module.

During the course of this chapter we will follow the information trail, beginning with raw data from several sensors and going all the way to filtered and processed information ready to be delivered to users in the form of a visualizer application (Figure 5.1.)

The information path starts with the sensing module, where relevant data is collected from several sources in the vessel. Then, using the networking module, the raw data is transported to the processing module, where it is logged, filtered, and processed. One or more visualizers connect to the server (also using the networking module) and establish a live stream of information that is displayed in real-time using the visualization module.

5.2 Sensing Module

The sensing module supplies the sensory capabilities of the system, e.g. telemetry readings, on-board instruments integration, cameras, battery readings, etc. There are four major categories of sensory sources, grouped as units, based on their hardware and integration into the vessel systems.

1. Telemetry Unit;
2. Imaging Unit;
3. Internal Unit;
4. Instruments Unit.

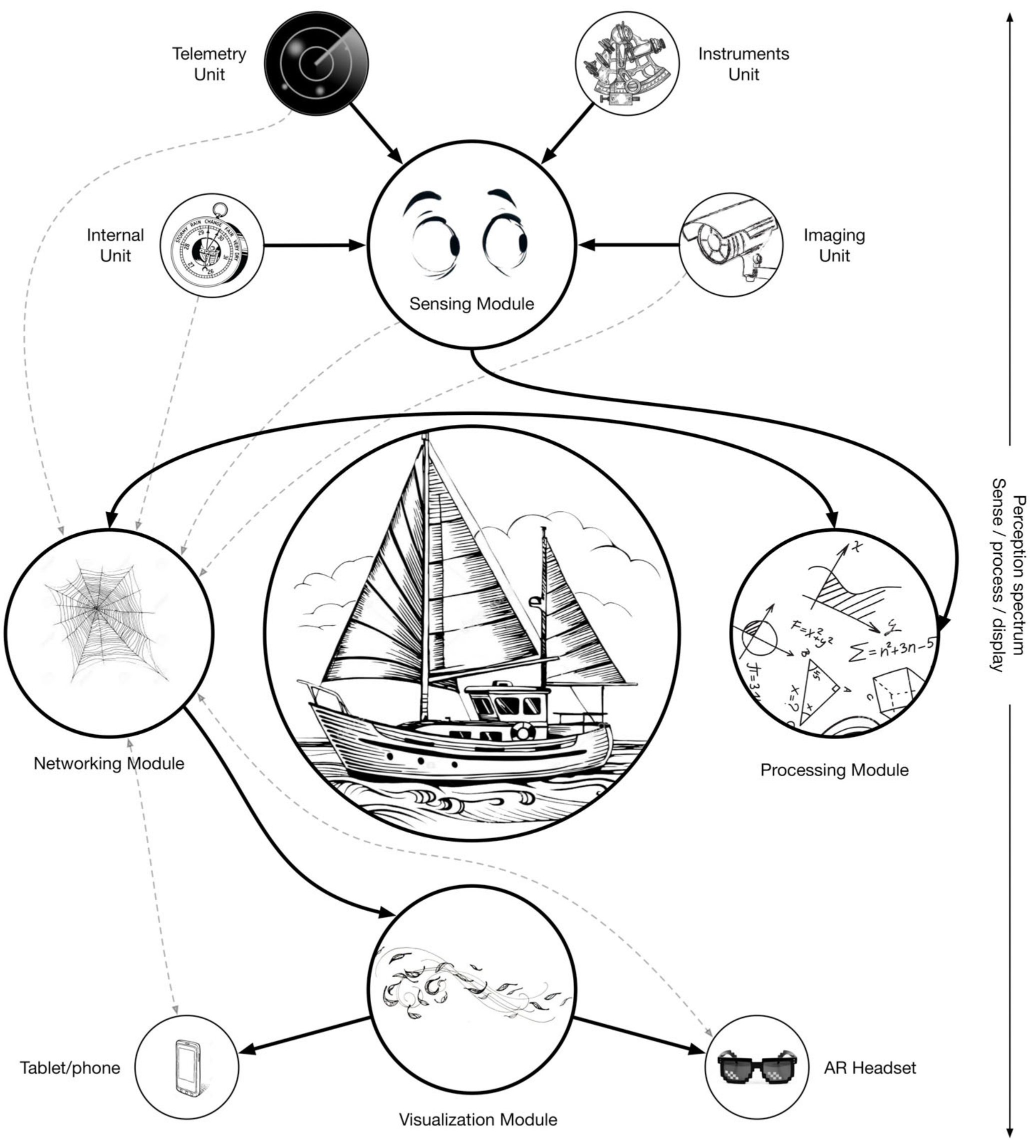


Figure 5.1: System Overview

5.2.1 Telemetry Unit

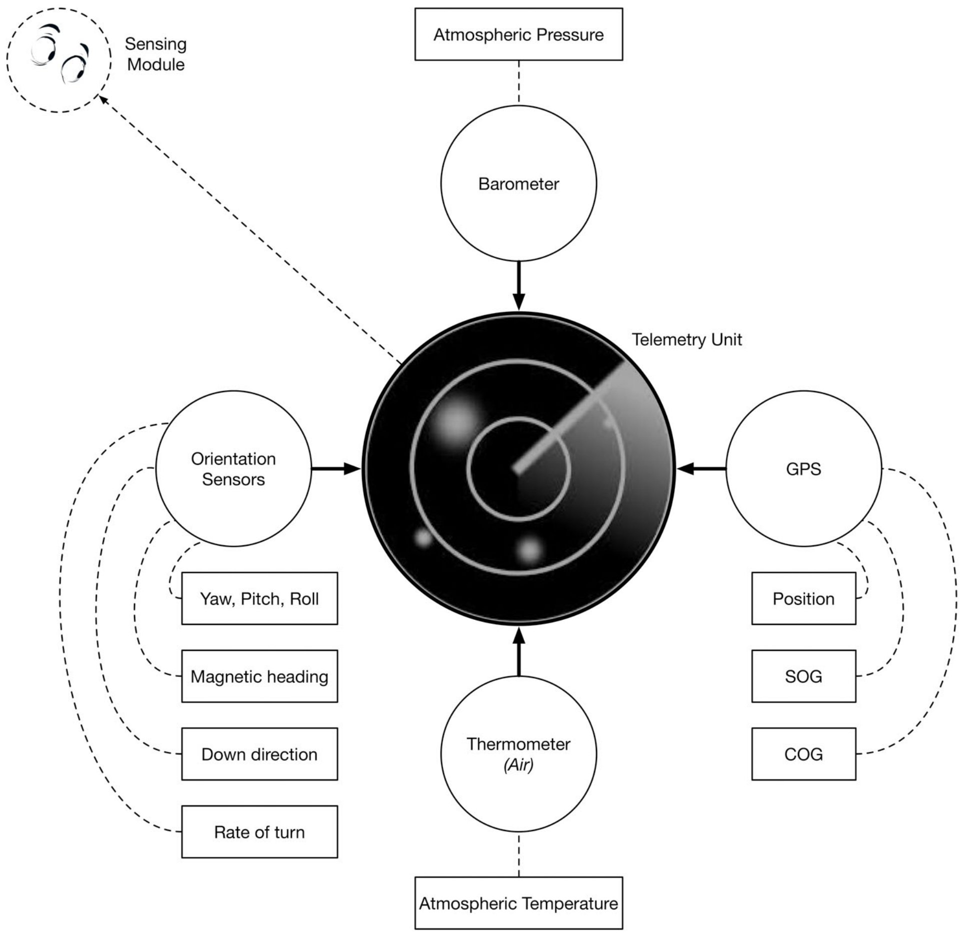


Figure 5.2: Telemetry unit components

The telemetry unit is a hardware assembly featuring a micro-controller and several sensors, all bundled together inside a sealed box, attached to the outside of the hull. It is placed at the intersection of the ship's central axes and it provides information about the boat's pose (position+orientation) and movement relative to the ground and the boat itself; it also provides environmental data such as atmospheric pressure and air temperature. The unit reads data from the sensors, maintains a permanent connection to the server, and constantly sends current data over the network.

GPS

The GPS sensor is a hardware component that provides information about the position and movement relative to the ground. The position is provided in degrees decimal minutes format (e.g. Lat. 64° 53.754' S, Lon. 69° 20.050' W). The movement is provided using speed over ground (SOG) and course over ground (COG) data.

Absolute Orientation Sensor

Absolute orientation readings are provided by a Bosch BNO55 sensor that supplies not only orientation information like roll, pitch, and yaw, but also in-depth readings like 3D magnetic heading or accelerometer/gyro data.

Barometer

The barometer provides atmospheric pressure data. This data is subsequently processed in order to provide information regarding the tendency of the atmospheric pressure readings.

Thermometer (Air)

The thermometer found in the telemetry unit provides data regarding the air temperature outside of the boat. The data is collected, logged, and used together with the barometric readings for micro-weather forecasts.

5.2.2 Imaging Unit

The imaging unit is an electronic component comprised of a micro-controller (Raspberry Pi 3) and two cameras, a main camera, and a night-vision camera. This unit captures a video feed from the cameras and streams it to the server. The micro-controller maintains a permanent connection to the server over the network and streams video content in real-time.

The main camera captures video content in the visible spectrum of light. The actual hardware is a Raspberry Pi Camera Module V2 capable of recording 1080p30 and it is connected to the CSI port on the Raspberry Pi.

The night-vision camera captures video content when there is little or no visible ambient light. The hardware used is a Raspberry Pi NoIR Camera V2.

According to the website raspberrypi.org: "The Pi NoIR gives everything the regular Camera Module offers, with one difference: it does not employ an infrared filter. (NoIR = No Infrared.) This means that pictures you take by daylight will look decidedly curious, but it gives you the ability to see in the dark with infrared lighting."

For research purposes, the cameras have been used interchangeably on the same micro-controller or using multiple micro-controllers. I do not plan to purchase an Arducam Multi Camera Adapter Module that will allow the use of two daytime cameras and two night-vision cameras with only one micro-controller. This would allow for both daytime and night-vision stereo-graphic video capture.

5.2.3 Instruments Unit

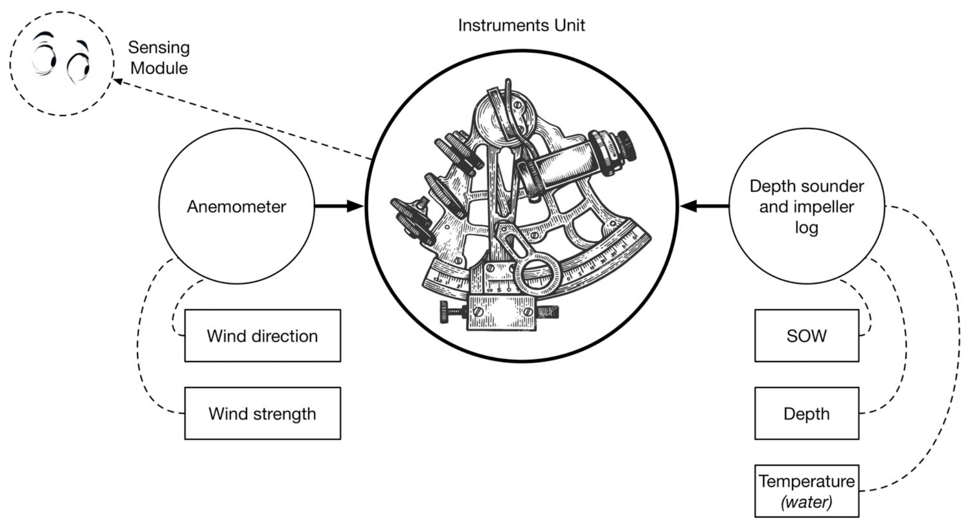


Figure 5.3: Instruments unit components

The instruments unit is an electronic component that allows the interfacing of various instruments and sensors already installed on the boat.

The unit can be seen as an interface between the NMEA2K/SeaTalk bus connecting the instruments and the boat server. For my purposes, I use a Garmin GND™ 10 Black Box Bridge that allows a direct USB connection.

The difference between the hardware in the instruments unit and the hardware in the other units is that the instruments are off-the-shelf products and are used on the boat independent of the ARVS System. In fact, there are several gauges and displays mounted in the cockpit that display such information such as wind speed/strength or speed over water, completely separate from the proposed marine visualization system.

Anemometer

An anemometer is an instrument used to determine the apparent wind direction and strength, relative to the motion and orientation of the boat. To better understand and emphasize the relative nature of the reading, let's consider the following scenarios: if the vessel is travelling downwind at 5kn, in 10kn winds, then the apparent wind is 5kn; yet, if the vessel were to go in the opposite direction, the apparent wind would be 15kn.

The anemometer sensor is wired into the GND 10 Black Box.

Impeller Log

An impeller log is an instrument used for determining the speed over water (SOW) - i.e. the speed of the vessel relative to the water; this is different than the SOG readings from the GPS unit, which reflects the speed relative to the ground below. By measuring the SOG and the SOW, I can estimate the speed and direction of the tidal currents the boat is travelling on. E.g. If the vessel is travelling with a SOW of 2kn over a current in the same direction of 3kn, then the SOG will be 5kn.

The impeller log sensor is wired into the GND 10 Black Box.

Depth Sounder

A depth sounder is an instrument used to determine the water depth under the boat. By computing the tendency of the water depth over time, the server can provide an estimate about the relative danger of running aground.

The depth sounder transducer is wired into the GND 10 Black Box.

Thermometer (Water)

The depth sounder transducer also features a thermometer to measure the water temperature.

5.2.4 Internal Unit

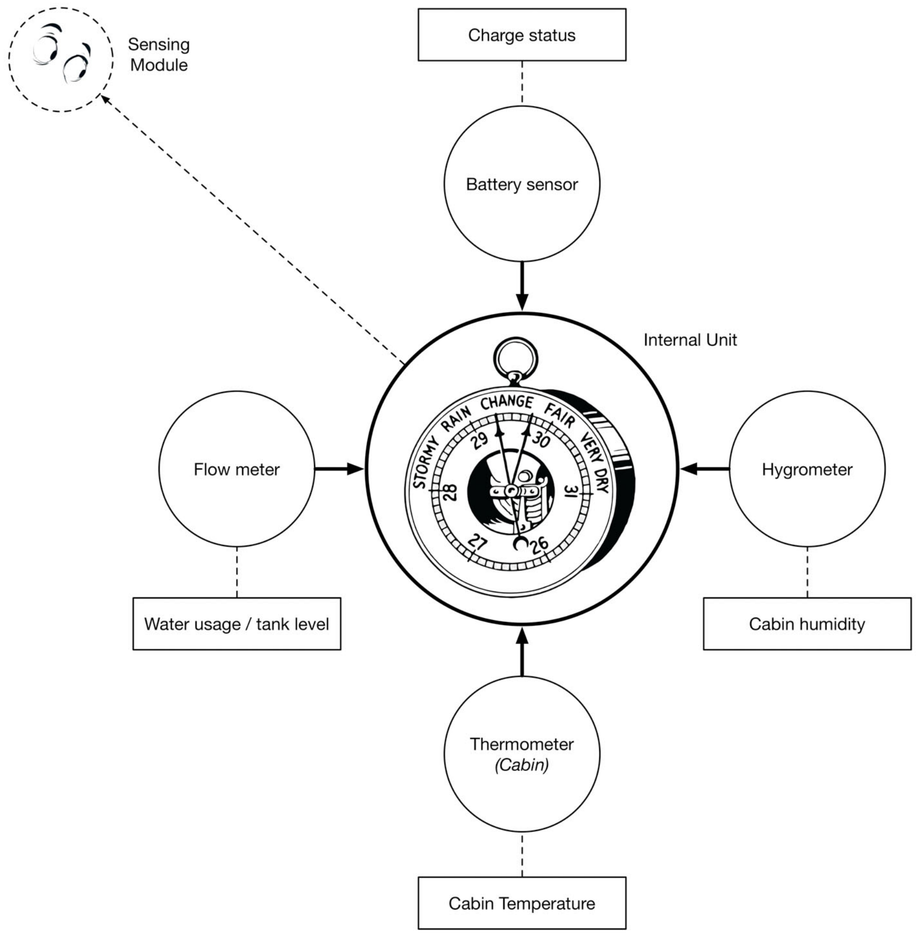


Figure 5.4: Internal unit components

The internal unit is a hardware assembly featuring a micro-controller and several sensors. It provides readings about various boat aspects (e.g. battery level, relative humidity, temperature, etc.) This unit is conceptually similar to the telemetry unit and it uses similar hardware, however it is targeted at internal aspects of the boat. The unit reads data from the sensors, maintains a permanent connection to the server, and constantly sends current data over the network.

Battery Sensors

The battery sensors are electronic components attached to the boat's batteries. They provide real-time information about the battery voltage and the current levels.

Hygrometer

The hygrometer is a sensor that provides readings about the relative humidity inside the boat. The relative humidity is important in determining estimates about potential biological hazards (e.g. In 40°C and 90% humidity mold starts developing in 24-48 hours).

Thermometer (Boat)

The thermometer found in the internal unit provides data regarding the temperature inside the boat. The data is collected, logged, and used together with the hygrometer readings.

5.3 Networking Module

The networking module is a collection of hardware resources that facilitate the transmission of data from one unit to another inside the system.

The topology of the network is radial, with the boat router in the center. Several devices connect to the router either via Ethernet, WiFi, Bluetooth or Xbee. The devices that form the sensing and processing modules are all allocated static IPs, while the devices that form the visualization module use DHCP.

Using the networking capabilites, the server connects to the rest of the devices either via Ethernet (router), WiFi (telemetry unit), Bluetooth (backup for the telemetry unit), USB (instruments unit), or Xbee (internal unit).

5.4 Processing Module

The processing module facilitates the real-time processing needs of the system (Figure 5.5). It is comprised of a server that receives data from the sensing module, processes the data, and transmits real-time information to

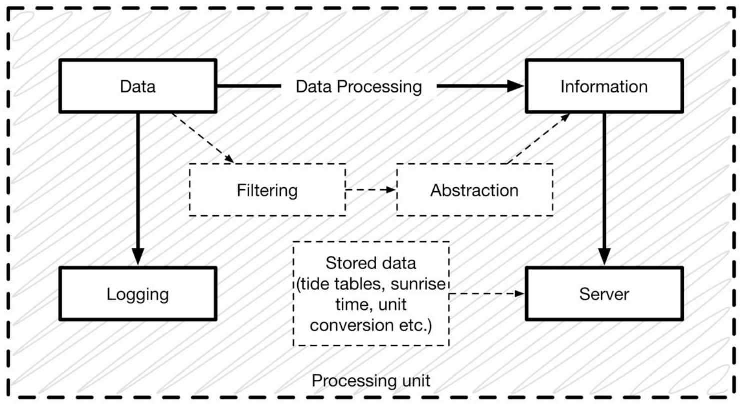


Figure 5.5: Processing module components

the visualization module. It also supplies the adjacent functionalities of data logging and network (http) server.

For the server we have used several mini-computers, including a Mac mini, an Wintel W8, and a Raspberry Pi. The server uses Debian Linux as an operating system.

5.5 Visualization Module

In the current section I explore most of practical aspects regarding the visualization effort. This includes hardware components, software technologies used, and conceptual considerations regarding the design of the visual interface.

The visualization module provides users with an augmented reality scene that is populated with real-time information from the processing module. The scene can be rendered in a browser on various compatible devices.

5.5.1 Devices

The visual information is provided to users via a browser installed on any device capable of rendering the real-time augmented reality scene. For my research purposes, I successfully tested the system on several devices including the following: Apple MacBook Pro, ThinkPad T40, RaspberryPi Ver. 3, ASUS Transformer Pad TF700, NVIDIA Shield Tablet, Sonim XP7, iPhone 6s. I found that most of the devices could handle the core visualization features, but only the MacBook, Raspberry Pi, and the Shield Tablet could run the more demanding particle cloud animations successfully.

5.5.2 Software

From a software perspective, my system can run on most of the current operating systems (i.e. Android, iOS, macOS, Linux, etc.). It requires a working browser and I have used the Chrome/Chromium browsers. The browser needs to be able to run HTML5, CSS, JavaScript, and WebGL. The scene is implemented using the Three.js library and API.

5.5.3 Visual Interface

The visual interface is the graphical entity that provides access to the augmented reality scene. It renders the scene by populating a scene template with real-time information streaming from the processing unit. The scene template is comprised of several different kinds of layers with a wide range of visual elements, which I will explore in Chapter 6.

5.6 Summary

This chapter provides a detailed account of the various elements that make up the system.

I introduced and explored in detail the main modules of the system: sensing (see 5.2), networking (see 5.3), processing (see 5.4) and visualization (see 5.5).

The sensing module is the most vast and complex and it is made up of four units: the telemetry unit (see 5.2.1), the imaging unit (see 5.2.2), the internal unit (see 5.2.4), and the instruments unit (see 5.2.3).

In the next chapter, 6, I will examine in-depth the different visualization aspects of my research.

Chapter 6

Visualization

"A sailor is an artist whose
medium is the wind"

Webb Chiles

This chapter discusses issues that pertain to the visualization process in general and the AR scene anatomy in particular.

Before going into the technical details, I introduce the way users interact with the system.

On the technical side, I start by identifying the different screen areas used. Then, I examine the perspective from which I see the AR content. Afterwards, I discuss a few different types of content appearance I considered using. Last, I explore the individual scene elements and the way they are represented as part of the scene structure.

The visual content I am proposing is by no means the best option one could come up with and, in fact, I have experimented with many different configurations with varying success. It would take several axes of interest and investigation of the actual graphical representations to determine what is most appropriate for a given set of user scenarios. My contribution is not centred on tweaking the actual visual content, but rather on creating a system by identifying and using known technologies and methods as well as proposing new ones, like pseudo-natural appearance (6.4.5) and content distortion (section 6.4.6).

6.1 User Interaction

Before examining the technical aspects of the system, I should shed some light on a few details about how users interact with the system.

6.1.1 Devices

The users are presented with a tablet (NVidia Shield Tablet) and a smartphone (Sonim XP8). Both devices are connected over a WiFi connection to the ship's server. Both the tablet and the smartphone have Velcro patches glued to their backs and they can be fixed to various surfaces in several places throughout the cockpit and inside the main cabin. The tablet is usually positioned in front of the steering well. It can also be attached to the wall in front of the chart table or in front of the galley, when the user is inside the cabin.

The smartphone is mostly used when the sailor is performing sail adjustments, weighing anchor, or performing other tasks on deck. The phone is sometimes held in hand and sometimes attached to the sailor's arm, between the wrist and the elbow using the Velcro material.

Both devices have the same AR scene rendered, but at different resolutions. The server provides a live feed of the video data captured by the bow camera that is synchronized with an information package that includes wind direction, heeling angle, and speed over ground among others.

The video that the user sees is not streamed, but rendered on the device, using web technologies including HTML5, JS, and WebGL, all inside a browser. The interface does not require installing a special app; instead it requires only a URL to load into a browser window.

6.1.2 User Input

To understand how the user interacts with the interface, I need to identify two different modes: interface configuration and real-time operation. For research purposes, I allow users to switch between these two modes.

In the configuration mode, users can access a menu, where various aspects of the interface can be configured.

In real-time operation mode, users do not directly control the interface using the input capabilities of the tablet, but rather using the sensing capabilities that have been added to the boat. User access the boat's mechanical devices to control the operation of the boat, which ultimately determines what the interface will display.

For example, when sailors make a 90 degree turn from a beam-reach to a wing-on-wing point of sail, the user interface will reflect the turn by changing all the displayed data to match the new situation.

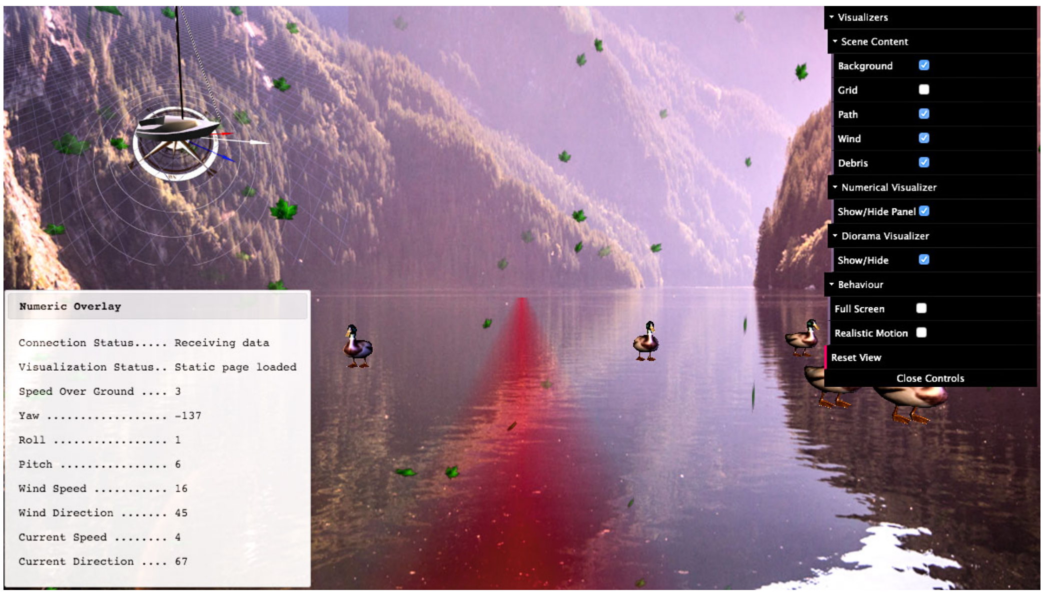


Figure 6.1: AR Scene

6.2 Screen Areas

The screen can be organized between different working areas, depending on the kind of content that will be displayed (Figures 6.1, 6.2).

- ☐ Main area (covering the whole screen with immersive content)
- ☐ Diorama (top left blending into the main area, bird's eye view of boat)
- ☐ Panels
  - – Numeric panel (all incoming data)
  - – Graph tendency (depth, atmospheric pressure)
- ☐ Menu (normally collapsed, expands when needed)

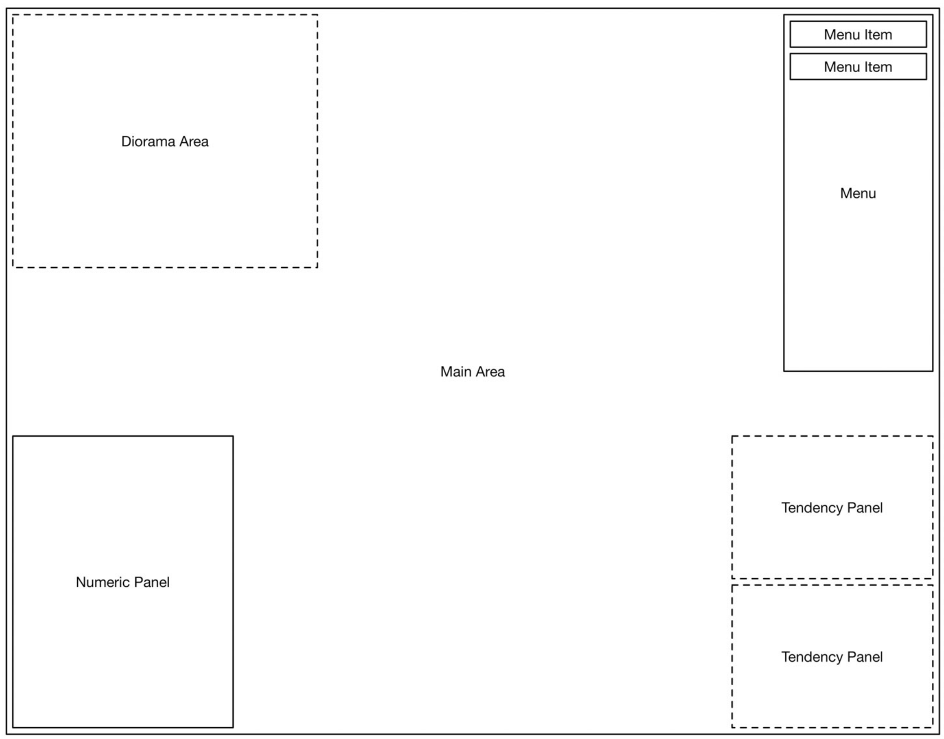


Figure 6.2: Diagram of screen areas

6.2.1 Main Area

The main area covers the entire screen and it typically features content where the live video-feed from the camera (used as a background) is synchronized with the overlayed virtual content that is distributed all around the viewer, creating an immersive feel (see Section 6.3.1).

It is possible for the content of the main area to be switched to a non-default perspective for specialized purposes, such as visually investigating the vectors (e.g. wind, current) that act on the boat.

Figure 6.3: Scene rendered using only the main and diorama areas

Often, the main area looks like the screenshot featured in Figure 6.3.

6.2.2 Picture-in-picture Area

The picture-in-picture (PIP) area is smaller, overlayed on top of the main area, and it features customizable size/position/transparency (Figure 6.4).

This kind of area features a transparent background that allows it to blend in with the main area; as such, it does not have a visible border. The perspective of the content of the PIP area is what I have called the Diorama perspective (Section 6.3.2).

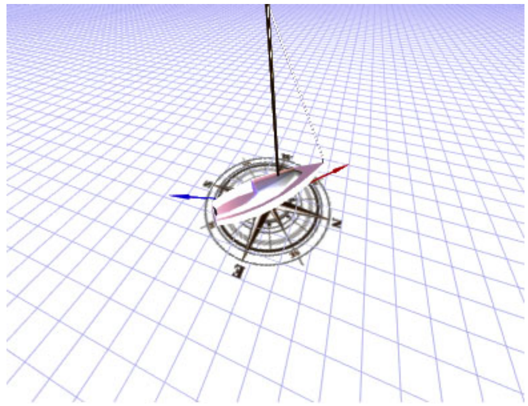


Figure 6.4: Standalone screenshot of the PIP area, with wind and motion vectors seen in blue and red

The content that is typically found in this area is of an abstract nature, including a grid synchronized with the ground, range rings, vectors representing the wind, current and motion, and an animation of the roll/pitch/yaw of the boat in real-time.

6.2.3 Panels

The panels are screen areas clearly defined by a border and/or background colour and they feature either numeric information or 2D tendency graphs (e.g. depth, barometric readings).

These areas stand out and hover above the main and PIP areas; they can be moved and turned on/off (Figure 6.5).

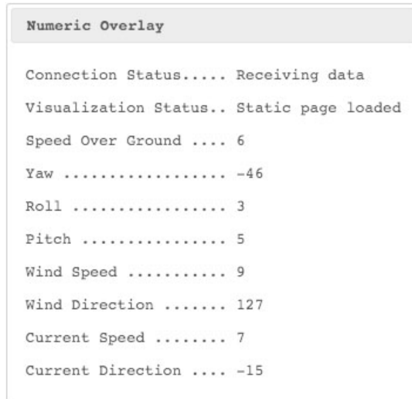


Figure 6.5: Numeric Panel

6.3 Content Perspective

Perspective is another important issue in discussing augmented perception. For my purposes, I identified the following two:

6.3.1 Immersive

In the immersive perspective, the virtual content is generated and synchronized both conceptually and visually with the background, which is a live video stream from the cameras. As such, the user sees what the boat sees and this view is augmented with virtual content, surrounding the viewer.

6.3.2 Diorama

In the diorama perspective, the camera has a bird's eye view of a scene with the boat in the centre and the virtual content displayed around it (Figure 6.4).

6.4 Content Appearance

In my approach, I distinguish between different methods of displaying data/information and this determines the appearance of the content. The numeric and graph methods are nothing new as they have been featured in visualization projects for decades. The natural appearance is what we see with our own eyes, so this topic, too, doesn't require much detail. The abstract method has been featured in such applications as car GPS systems in the form of either motion indicators or waypoints/direction markers. In my project, however, due to the highly complex nature of the propulsion, a solid understanding of the environment requires a complex abstraction model as resulting graphical representations. In the last method, the pseudo-natural appearance is the crux of my research. It is content that looks and behaves like natural content, but has one vital clue to make it obvious to users that it is virtual.

6.4.1 Numeric Appearance

The numeric content is exactly that, information displayed in numeric form (Figure 6.5).

6.4.2 Graph Appearance

As for the graph content, it tracks the tendency of various entities over time (e.g. depth) in visual 2D form, but without registering it in the spatial context of the augmented reality content.

6.4.3 Natural Appearance

In the immersive perspective (6.3.1), the content is made up of the background video-feed coming from the cameras and overlayed by the virtual content. All of the virtual content is related to the background video and it is registered into the adjacent spatial context generated based on sensor data (e.g. boat orientation, heading, etc.).

In this context, by natural content I refer to the video stream coming from the cameras. For example, if there are visible features (e.g. debris on the water, shore etc.) and the boat is in motion, I can derive the direction of movement of the boat based on the appearance of the features: if they are moving from the top of the screen towards the bottom, then the boat is moving forward. Also, the features themselves (e.g. a floating log) have the actual meaning they have in real-life, as opposed to the pseudo-natural content, as seen below in Section 6.4.5.

6.4.4 Abstract Appearance

By abstract content I refer to a series of abstract visual representations (e.g. arrows) that are used to represent information on a higher conceptual level. For example, I could represent the wind direction and strength relative to the spatial context by displaying an arrow with a certain orientation and length inside the virtual scene (see Figure 6.4).

6.4.5 Pseudo-natural Appearance

We introduce the concept of *pseudo-natural appearance* as content that mimics the natural appearance and behaviour of an entity, but with a distinctive visual or conceptual component that makes it immediately recognizable as virtual content. The concept is related to that of biomimicry [57]. Using pseudo-natural content can create a synesthetic visual effect, where information from non-visual sources can be displayed in a visual medium.

Figure 6.6: Pseudo-natural appearance: ducks with feet on the surface of the water

For example, on the West Coast it is quite common to see Canada geese on the water and this would be considered natural content. If, however, we were to see a flock of rubber ducks in our scene displaying the same behaviour as Canada geese, we would think that the entity represented by the flock is akin to actual geese in behaviour, yet it is obviously made of virtual objects.

In Figure 6.6 we see a couple of ducks used as content with a pseudo-natural appearance. The ducks are supposed to look realistic, yet the virtuality clue is their feet. If the ducks are standing on their feet, making the feet visible, then they have to stand on a solid surface, not on water. But if the ducks are floating on the surface of the water, then their feet will not be visible. This clue should make even in a photo-realistic rendering of the ducks obvious to viewers that they are, in fact, virtual content.

I propose the use of pseudo-natural (PN) appearance to create a kind of content that is visually easier to comprehend than an abstract representation of the same underlying information.

Natural and pseudo-natural content is visually and mentally assimilated in similar ways, in contrast to abstract content, which requires significant mental effort. For example, if one sees leaves blowing in the wind, one processes the wind direction differently that one seeing a numeric representation of the wind direction in degrees.

6.4.6 Distorted Content

Another concept I would like to explore is that of distorted content, designed to trigger an usual conceptual or emotional response.

Spatial Distortion

In Figure 6.7 we see a warped space effect whereby the boat seems to slide towards and up the red line, which indicates the estimated route. In this example I used a grid and a red path to accentuate the effect, but normally it would be only the background image that is warped, creating a more natural, milder effect.

I used this effect only on the background image, but I can easily warp the spatial coordinates of the scene to illustrate attraction or repulsion. For example, if there's a known threat, I could warp the background and also the placement of the object in the virtual scene to provide hints to steer away from the hazard.

The idea of designing content that stimulates a feeling of attraction or repulsion was inspired by an art piece created by the conceptual artist Derk Wolmuth, in which by manipulating spandex to form a gravity-well-shaped object, a viewer would feel like they're being pulled in (see Figure 6.8).

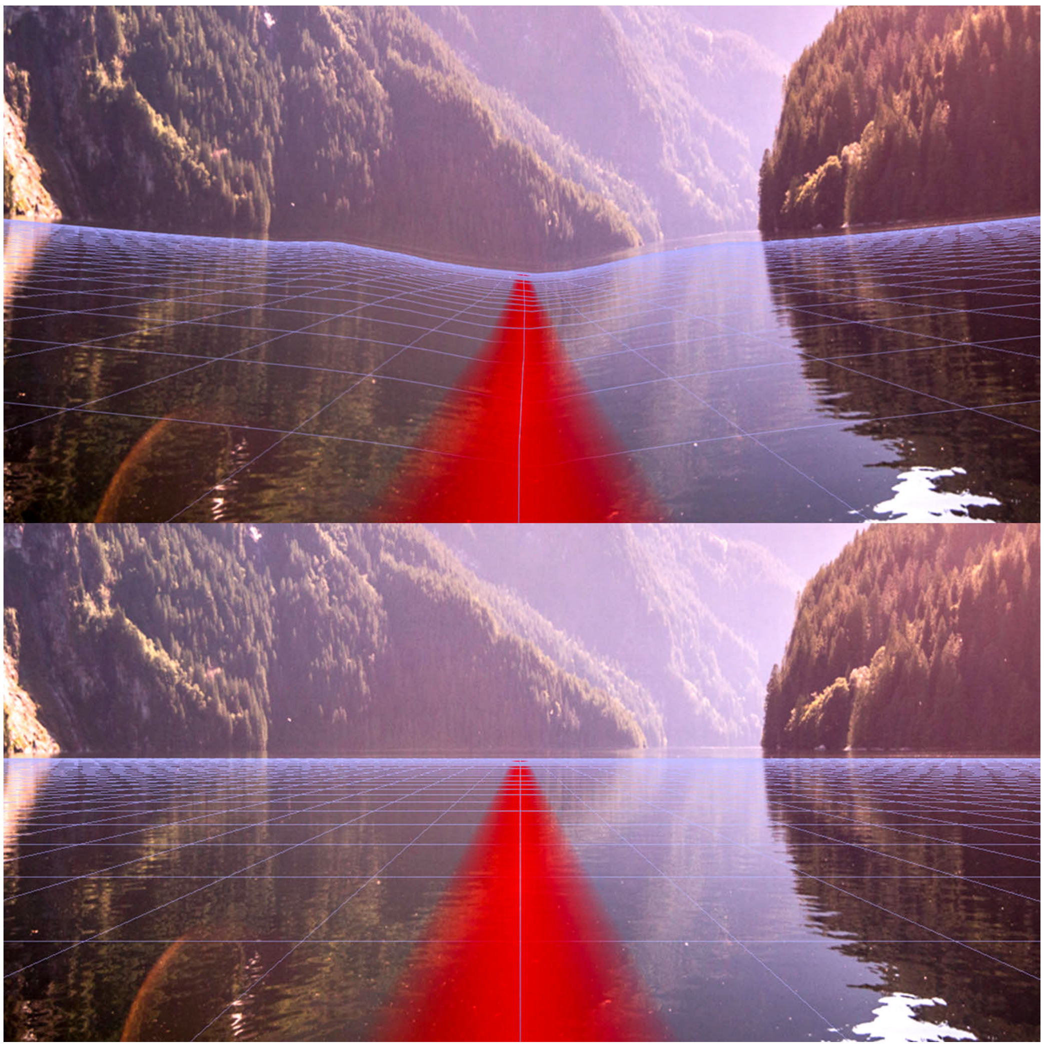


Figure 6.7: Bottom: original space. Top: warped space.

Figure 6.8: Gravity well by Derk Wolmuth

Shape Distortion

If I want to give a certain shore feature or rock wide berth, I could distort the shape of the actual feature to highlight the danger. For example, I could make the height of a drying rock three times higher.

Colour Distortion

The appearance of a scene entity could be manipulated from the perspective of colour. Excessive heeling could be visualized using a red haze layer toward the peripheries of the screen, with transparency proportional to the heeling angle, as seen sometimes in computer games.

To achieve PN appearance, particle clouds mimicking bio-luminescence could have a colour that is implausible (e.g. white or gray).

Perspective Distortion

Illustrating excessive motion can be achieved using a method of distorting the perspective.

For example, for excessive heeling in coastal cruising, the motion of the boat in the diorama area could be exaggerated by a factor to increase the awareness. Also, the background image could be rotated to exaggerate the motion.

On the other hand, in open ocean sailing sometimes sailors get seasick while below decks and a powerful tool to fight this is simply seeing the horizon, either naturally, out the window, or using our system. Even more, zi could play down the visual swaying using the sensor data, which may reduce sea-sickness.

6.5 Content Organization

In this section I will explore the different kinds of content we will encounter in our scene. Please see Figure 6.9 for a diagram of the scene content.

6.5.1 Background

The background video is made up of live content captured by the bow-mounted camera(s).

6.5.2 Motion

Motion content:

- ☐ Main: pseudo-natural ducks (speed)
- ☐ Diorama: vector (direction, speed), grid moving backwards
- ☐ Panel: numeric (direction, speed)

An old method of estimating the speed of a boat over water was to throw some object in the water at the bow and measure how long it takes for it to clear the stern. Our take on this method is to place artificial debris in the water, to simulate the boat's passing relative to the debris, and therefore to generate an impression of motion. In the screenshots I used ducks instead of debris.

6.5.3 Orientation

Orientation content:

- ☐ Diorama: model boat orientation (pitch, roll)
- ☐ Panel: numeric (yaw, pitch, roll)

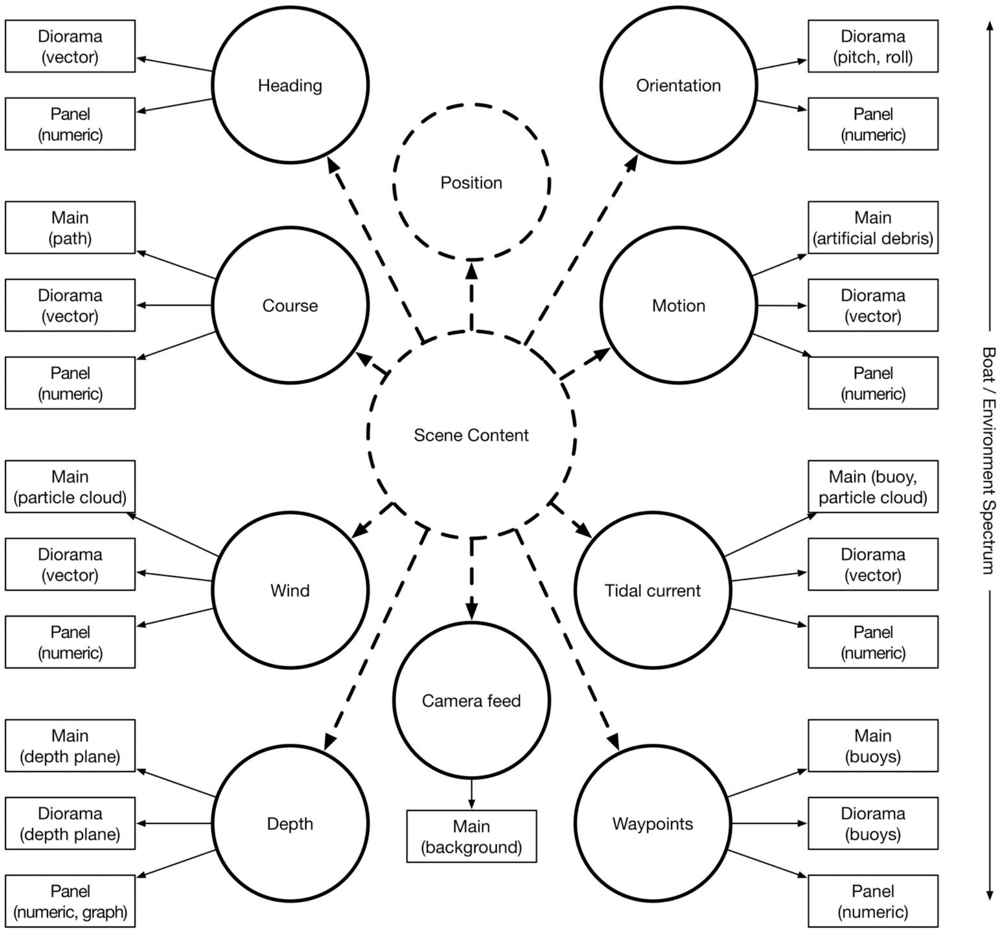


Figure 6.9: Scene content

6.5.4 Course

Course content:

- ☐ Main: highlighted path, warped background
- ☐ Diorama: vector (direction, speed)
- ☐ Panel: numeric (direction, speed)

6.5.5 Heading

Heading content:

- ☐ Diorama: vector (angle)
- ☐ Panel: numeric (angle)

6.5.6 Wind

Wind content:

- ☐ Main: leaf-based particle cloud (direction, speed)
- ☐ Diorama: vector (direction, speed)
- ☐ Panel: numeric (direction, speed)

6.5.7 Tidal current

Tidal current content:

- ☐ Main: artificial kelp floating with the current
- ☐ Diorama: vector (direction, speed)
- ☐ Panel: numeric (direction, speed)

6.5.8 Depth

Depth content:

- ☐ Main: depth-plane rising as warning (depth)
- ☐ Diorama: depth-plane (depth)
- ☐ Panel: numeric (depth), graph (depth tendency)

6.5.9 Waypoints

Waypoints content:

- ☐ Main: buoys (within a local horizon)
- ☐ Diorama: buoys (within a local horizon)
- ☐ Panel: numeric (distance and bearing to next waypoint)

6.6 Summary

In this chapter we saw an systematic recount of the visual aspects that determine the content of the AR scene in support of the visualization effort.

First, we looked at the different screen areas that form the visual interface: main area (see 6.2.1), picture-in-picture (see 6.2.2) area and the panels (see 6.2.3).

Then, we explored two perspectives from which the content can be created: immersive perspective (see 6.3.1) and diorama perspective (see 6.3.2).

Next, I discussed different ways of approaching the visual appearance of conceptual content: numeric appearance (see 6.4.1), tendency graph appearance (see 6.4.2), natural appearance (see 6.4.3), abstract appearance (see 6.4.4), pseudo-natural appearance (see 6.4.1), distorted content (see 6.4.1) and conceptually metamorphic content (see 6.4.1).

And last, I created a structure that keeps track of the various types of content I use for the visualization (see 6.5. Among the content elements, the most notable are the background, the wind and current, motion and orientation and course and heading.

Next, in Chapter 7, I will employ a design system that starts by investigating the conceptual background for my research and continues to refine and correlate findings gradually, until I obtain an emergent set of conceptual and design principles which, ultimately, materialize in the form of system features and specifications.

Chapter 7

Solution Analysis

> "I must be a mermaid, Rango. I have no fear of depths and a great fear of shallow living"
>
> *Anais Nin*

This chapter discusses the solution and the entities that enter into the scope of relevance for our design. The examination in this chapter addresses the effort of drafting a blueprint of the solution. It is one of the most important contributions in this dissertation, and certainly the most voluminous.

Together with Chapter 4, this chapter recounts the design process that led to the system implementation presented in Chapter 5 and Chapter 6. While Chapter 4 explores the design iterations and choices that led to the latest problem/solution statement, this chapter focuses on the individual concepts that form the solution and the conceptual relationship among them.

7.1 Overview

Many of the terms used will be familiar to a reader versed in Design Thinking [58].

I will start by ,discussing the role observations played in the design process. Next, I will cover most of the important insights I derived from an extensive analysis of the underlying study.

I will explore insights from several sources, including sailing and geophysical aspects, perception and ergonomics, human-computer interaction and visualization concepts.

Then, using these insights, I will propose a set of conceptual principles that explain *what* I am trying to achieve by understanding *why* I am trying to achieve them. In fact, this will be the meaning of the arrow symbol I use in my diagrams (Figure 7.1). The study of the causal relationship [59] between the various entities in this chapter should be seen from the perspective of theoretical philosophy and, in particular, conceptual modelling [60] and ontology [61], rather than design thinking.

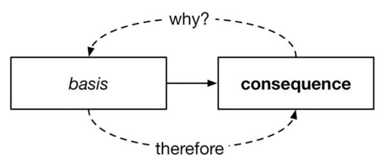


Figure 7.1: Meaning of arrow in diagrams: Basis and consequence

Afterwards, starting off from the conceptual principles, I will draft a set of design principles that will determine what system features will be implemented. The detailed description of the system features will form the basis for the actual implementations; I will recount this last stage as specifications.

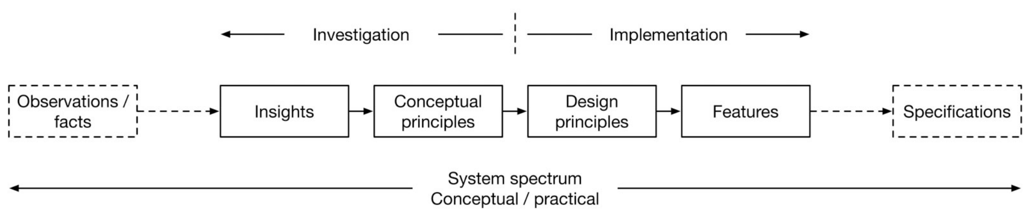


Figure 7.2: Overview of the design process pipeline

The conceptual flow, starting from observations, through insights, principles, features, and ending with specifications is formalized by using keyed tables of entities and dependencies/relations. A simplified graphical representation of the conceptual flow can be seen in Figure 7.2. The design process spans a conceptual/practical spectrum and the two halves of the spectrum denote the investigation and implementation efforts on the left and right side, respectively.

The physical specifications of the system are covered in the Chapter 5, while the conceptual specification of the AR scene implementation are featured in Chapter 6.

Please see Figure 7.3 for a detailed diagram of my implementation of the design process pipeline [58].

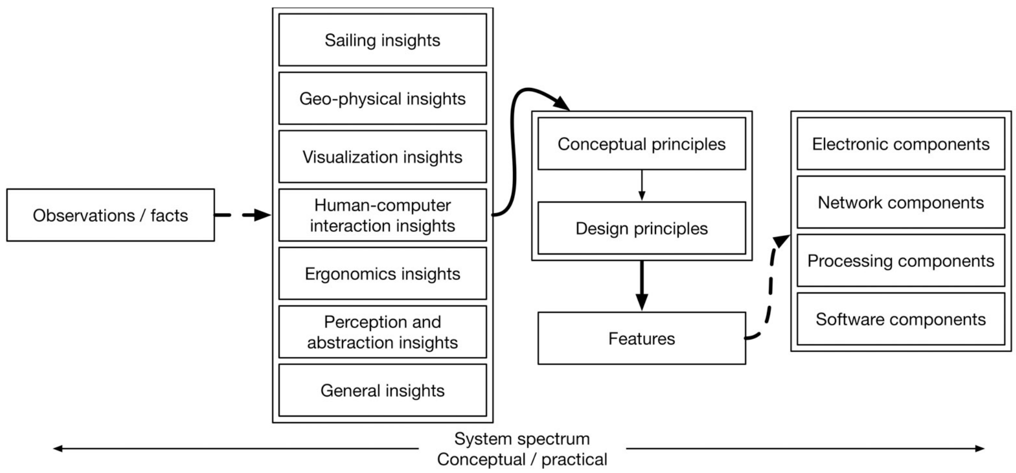


Figure 7.3: The design process pipeline

7.2 Observations

The Oxford English Dictionary defines the term "observation" thus:

> "The action or an act of observing scientifically; esp. the careful watching and noting of an object or phenomenon in regard to its cause or effect, or of objects or phenomena in regard to their mutual relations. [...]"

For my purposes, I will understand the concept of *observation* as simply *what I saw, heard, or thought. A fact.*

During my research project, I collected many observations and relevant facts which I compiled to support the derivation of insights by understanding the context, performing conceptual prototyping, developing mechanical, electronic, and software implementations.

I also devoted considerable effort to investigating existing cognitive science papers, journals, and other published materials that informed many of my design decisions from the perspectives of epistemology, perception, and cognitive science.

It would be well beyond the scope of this document to include all of the observations I collected, so I will only mention a few of the most important sources:

- ☐ **User Feedback.** I consistently consulted over time with users with diverse backgrounds and collected their opinions on a wide range of relevant topics (e.g. sailors, visualization researchers, mechanical engineers, electronics specialists, software experts, etc.).

- ☐ **Brainstorming Sessions.** I organized several brainstorming sessions to support the initial creative process for several components of the system, most notably the autopilot & PID Controller, the visualization interface and the conceptual background for important sections of my research.

- ☐ **Presentation Discussions.** After every public presentation, I recorded the questions and suggestions members of the public offered.

- ☐ **Sea-trial Reports.** During sea-trials, I used recording devices to exhaustively document details that I would have lost otherwise. Once in port, I compiled transcripts. Later, I analyzed these transcripts to generate detailed sea-trial reports.

  Please see Annex 9.2 for an example of a sea-trial report.

- ☐ **Research Journal.** I kept a research journal that documented the most important events of this project. In fact, I drafted Chapter 4 following the chronological events documented in my journal.

During all of the phases of this research project, collecting and documenting observations proved to be vital task. My documentation was an invaluable source for the subsequent steps in the solution investigation process.

7.3 Insights

Before I discuss my insights, I need to explain how I use the term.

The Oxford English Dictionary defines *insight* as:

> "The fact of penetrating with the eyes of the understanding into the inner character or hidden nature of things; a glimpse or view beneath the surface; the faculty or power of thus seeing."

And the Merriam-Webster dictionary defines it as:

> "1 : the power or act of seeing into a situation: to penetrate;
> 2 : the act or result of apprehending the inner nature of things or of seeing intuitively."

Within the scope of my research, I use the term "insight" [62] with the same meaning and connotation found in the process and theory of Design Thinking.

I identified a few themes I use to structure my insights:

- ☐ **Sailing.** Insights about the process of sailing.
- ☐ **Geo-physical.** Insights about geo-physical phenomena.
- ☐ **Perception and abstraction.** Insights pertaining to perception and abstraction.
- ☐ **Visualization.** Insights about visualization aspects.
- ☐ **Human-Computer Interaction.** Insights relevant for interface design.
- ☐ **Ergonomics.** Insights about the use and efficiency of various interface elements.
- ☐ **Art.** Insights from literature, photography, and cultural phenomena.

In the following sections, I will discuss an array of insights, which I will use later to derive conceptual principles. I will use those conceptual principles to synthesize design principles, the precursors to the actual system features. For this reason, I will cover the insights only briefly, without providing unnecessary details, focusing more on the relation they bear to their corresponding conceptual principles. For a complete list of the insights, see Table 7.1.

A few of the more important insights make assertions that seem to require validation. Wherever possible, I cited the sources. In the other cases, I based these insights on common sense.

7.3.1 Sailing Insights

These insights relate to various aspects of sailing including sources of information, heeling, electronics malfunction, the role of a first mate, situational perception, etc.

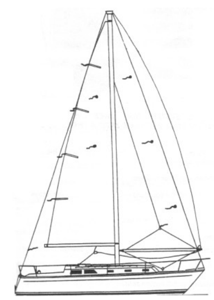


Figure 7.4: Sailboat Telltales

S1. The captain, the vessel and the sea

The process of sailing involves a captain being in control of a ship at sea. The captain needs to recognize and know how to interpret the countless eclectic aspects of the surrounding environment [63] (e.g. wind, tidal currents, etc.) The captain also needs to be intimately familiar with the boat's systems and how to control them.

Among these systems, the propulsion (e.g. sails), steering (e.g. rudder), and navigation (e.g. chart-plotter) are the most important. Access to information regarding the status of these systems, either through the senses or mediated by technology, is paramount.

S2. Data Sources

Sailors need access to data from a diverse range of sources (e.g. depth sounder, wind indicator on mast, sail telltales, tidal charts, current atlas, heeling angle indicator, etc.)

It is quite often overwhelming to get easy access to information. Unfortunately, it usually leads the captain to shift his attention from other, sometimes vital activities. [64]

S3. Heeling Danger

Heeling on a sailboat occurs naturally and is inevitable, yet it can be dangerous (Figure 7.5). Sailors routinely monitor how much the boat is heeling and take action in order to prevent capsizing [65].

The strategies for addressing over-heeling may be counter-intuitive to inexperienced sailors, like steering to weather which actually increases the heel for a moment, before going in irons. Seasoned sailors know from experience how to predict excessive heeling.

Figure 7.5: Dangerous Heeling

S4. Electronics Malfunction

Electronics are a valuable source of information for sailors, however, they often have malfunctions and when these occur, they can lead to catastrophic situations (e.g. lightning strike, Figure 7.6). While marine electronics are usually built ruggedly, according to strict regulations, they seldom have back-ups (e.g. GPS chart-plotters). Redundant systems are prohibitively expensive and rarely implemented. Sailors could benefit from secondary or tertiary sources, in case of electronics failures.

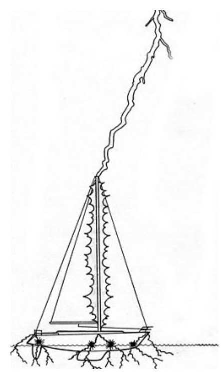


Figure 7.6: A lightning strike can fry the electronics and/or captain

S5. First Mate

Traditionally, one of the duties of a first mate was to disagree with the captain when the circumstances called for it [66]. This was a mutually beneficial and positive interaction, because the first mate would thus make the captain aware of his blind-spots in reasoning or action. The captain is still in charge and has the last word, but he is better informed because of the disagreement.

What we can take from this is that the first mate wouldn't make obvious observations, because the captain, being more experienced is already aware of them. The information the captain is presented with is targeted towards his blind-spots - it has to be focused and meaningful, not redundant.

S6. Non-linear Perception

> "The wind blows harder the closer you get to the mountaintop."
>
> *Leland Owlsley,* Marvel character

This metaphor was initially intended to hint at power-struggles, yet we found it to be reminiscent of the feeling one has when sailing in stormy seas.

The lighter the wind, the easier it is to sail, but when the wind starts to pick up, the captain is increasingly challenged by the situation. In fact, the attention demanded of the captain rises exponentially relative to the wind strength. While 20kn winds is smooth sailing, the situation increases from demanding, to very demanding, to outright scary from 25, to 30 and to 35kn winds respectively. I will leave the experience of Antarctic winter storms of 45-60kn winds to our heroes, like Shackleton [67] and his crew of 6 aboard the 22ft lifeboat James Caird (Figure 7.7a).

(a) (b)

Figure 7.7: Voyage of the James Caird: (a) departing Elephant Island, (b) approaching South Georgia Island

This observation, however, does not only apply to the wind, but also to currents and wave height. When all are combined, the captain is holding on for dear life.

7.3.2 Geo-physical Insights

The following insights address geo-physical aspects, in particular wind estimation, motion assessment, or tidal current estimation.

G1. Wind Estimation

Using their tactile sense, experienced sailors can feel and estimate the wind direction and strength on their faces or on the backs of their necks. Modern

Figure 7.8: The puppy's hair can be used to estimate the wind direction and strength

sailing equipment, like anemometers, use a wind sensor and a display to relay wind information either in numerical form or using rudimentary arrows and other 2D representations [68].

Humans cannot see the wind, but they can see the effects of the wind on observable entities (e.g. trees, leaves, ripples on the water, or an adorable puppy as in Figure 7.8).

G2. Motion Assessment

Considering the typical speeds of humans, we can seamlessly be aware of movement and motion through the kinesthetic and vestibular senses. When developing virtual content for AR or VR applications, we cannot tailor this content for the visceral senses that evaluate motion and, instead, we rely on visual cues to create the impression of motion.

On a light-wind day it is very hard to estimate the motion of a sailboat, even with one's own senses, let alone solely relying on visual interpretations. A floating piece of debris slowly passing by can be an invaluable source of information.

s 

Figure 7.9: The tilt of an anchored floating object can help us estimate tidal current direction and strength

G3. Tidal Currents

We can estimate the tidal currents for a large zone using tools such as a current atlas or marine chart in conjunction with local tide tables. Determining the tidal current behaviour for a certain location, however, is almost impossible. In stretches of water prone to currents, it is possible to estimate visually that there is a strong current, but the direction of the current is difficult to predict.

The most reliable ways to help us estimate the current direction is by observing either the direction of the turbulence around a shore feature (e.g. a day-marker or a rock, Figure 7.10) or the inclination and direction of an anchored object (e.g. buoys, Figure 7.9).

7.3.3 Visualization Insights

In this section I encountered a set of insights that approach visualization considerations.

V1. Rubber Duckies

Rubber ducks have proven useful in scientific visualization endeavours time and time again.

Figure 7.10: The shape and position of the turbulence provides clues about the current

Scientists from NASA's Jet Propulsion Laboratory have used rubber ducks to visualize the melt rate and motion of the Jakobshavn glacier in Greenland [69].

In an unrelated socioeconomic research project, published in the book, "Moby Duck", Donovan Hohn went on a journey of discovery trying to trace the origins of a huge batch of rubber ducks lost at sea during a storm [70].

V2. Representation Ambivalence

During one of my presentations, several people approached me with seemingly conflicting notes on visualization preferences. Some liked the immersive quality of using particles to visualize the wind. At the same time, others liked arrows much more.

On further investigation, I realized that the latter preferred a more abstract representation because they were experienced sailors and were used to navigating with existing products. The former were largely non-sailors and they favoured the immersive particle clouds because they seemed more intuitive and did not look cumbersome or hard to use.

V3. Way-points

Wiser sailors have learned to do their route planning homework ahead of time, while the rest of us wing it while already underway. If a desired route is known in advance, then it can be exported in the form of a series of way-points [71]. If these way-points could be integrated in the system and included in the visual experience, then the sailors could hold the desired course much more easily.

7.3.4 Human-Computer Interaction Insights

The following insights address a series of topics commonly found in the field of human-computer interaction research.

H1. Meta-Information

In order to fully understand how I want to use available augmented reality technologies, I must first start with the concept of meta-information, which is information about some aspect of a particular entity.

Figure 7.11 is an excellent instance of the use of meta-information: the text on the t-shirt introduces new information about the subject, while the subject himself presents it. The meta-information is self-contained. In this particular case, the context also confirms the meta-information, so the meta-information is also self-validated. In a way, this example of meta-information is actually meta-meta-information.

Figure 7.11: Example of self-contained and self-validated meta-information

H2. Three Scenarios of AR

1. Let's consider this first scenario: today, the most common understanding of AR technologies is that of AR glasses, with the Microsoft HoloLens being an excellent example. For these kinds of devices, the video feed is captured with one's own eyes and the virtual content is overlayed using various kinds of projections. The user and the capture device are one and the same and therefore there is only one perspective to consider. The user controls the perspective of the virtual content by pointing his head or eyes in a certain direction.

2. For the next scenario, I will take a tablet or a phone and point it towards some object. The video feed comes from the camera and is displayed on the screen. The user sees real and virtual content that is relative to the phone's perspective, not the user's perspective. The user has control over the perspective of the virtual content by pointing the AR device in a certain direction.

3. In the last scenario, I use a camera on the bow of a boat and then display the video feed on a screen set up in a different location. Now I have three different perspectives: that of the bow camera, the display, and ultimately that of the user. The user doesn't have control over the perspective at all; the virtual content is relative not to the user's perspective, nor to the display's perspective, but to the boat's.

H3. Bird's Eye View

A bird's eye view representation of an object can be a powerful aid to certain abstract processes. A classic example of this comes from physics in the form of a graphical representation of the composition of forces for an object on a slope. Using a similar approach, but in 3D, we can see the forces that affect a vehicle, as in Fig. 7.12.

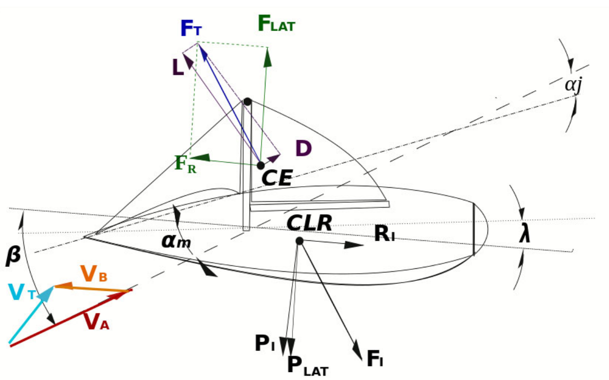


Figure 7.12: Example of a bird's eye view of a sailboat

H4. To each Media, their own Representation

The captain plots a course on a chart by using precise numeric readings from the instruments. A particle cloud representation of the course would be useless.

An abstract visual correlation between the vectors representing the movement over water relative to the movement over ground is inevitable for calculating the drift.

A certain barometric value is meaningless, but the barometric tendency is vital in forecasting the weather.

The depth tendency is important, but only when also knowing the actual depth; if it rises by 10 fathoms at a depth of 1000 fathoms it's insignificant, but a rise of 1 fathom at 3 fathoms of depth may signify imminent grounding danger.

In turbulent waters, estimating the current direction is vital, but monitoring the current tendency would serve no purpose.

There are no general solutions. The various media simply have their own specialized uses and representations.

7.3.5 Ergonomics Insights

I formulated a few insights based on ergonomic considerations, particularly the separation of planning and navigation and seasickness/anxiety reduction.

E1. Navigation/Planning Separation

Existing navigation products like digital chart-plotters try to accomplish both the task of planning and navigation at the same time, not performing either as well as they could. When navigating (i.e. sailing for the next little while), we do not need to see information in the interface that is not immediately relevant.

E2. Seasickness Reduction

Seasickness is a common occurrence for many sailors when below deck, especially in rough seas. Observing the horizon usually alleviates the sea sickness. If seasick sailors were to have access to a visual representation of not only the horizon, but also the motion of the vessel using a screen [72], this could prove beneficial to achieving the same benefits as actually observing the horizon outside.

E3. Anxiety Reduction

Having early warning features for various aspects of the system can alleviate anxiety. If the system can predict that the boat will heel too much before it actually does or predicts an incoming storm, it would reduce crew's anxiety. In the particular case of depth tendency warnings, this feature is well known to be invaluable to reducing anxiety [73].

7.3.6 Perception and Abstraction Insights

We have devoted considerable attention to several insights regarding abstraction and perception, which aided us to better understand various aspects relating to the nature of human thought and practice, in particular regarding perception and visualization.

P1. Abstraction

> "Always make a definition or sketch of what presents itself to your mind, so you can see it stripped bare to its essential nature and identify it clearly, in whole and in all its parts, and can tell yourself its name and the names of those elements of which it is compounded and into which it will be dissolved.
>
> Nothing is so conducive to greatness of mind as the ability to subject each element of our experience in life to methodical and truthful examination, always at the same time using this scrutiny as a means to reflect on the nature of the universe, the contribution any given action or event makes to that nature, the value it has for the whole[...]"

Mediations, Marcus Aurelius, Book Three, 11

Our research relies on a strong understanding of the surrounding environment and the boat's behaviour. These are complex entities that require a systematic breakdown into individual components and reintegration into an abstract model [74].

P2. Representation Model Accuracy

In the paper "The diverse aims of science" [75], A. Potochnik argues that in the quest for scientific understanding, we need to simplify and idealize models in order to make complex phenomena more intuitive and easier to understand. An excessively idealized scientific model is not helpful.

A model must pass a threshold of truth (i.e. it needs to be true enough for our purposes), but beyond that point, adding true details will make the model more difficult to understand. Understanding is more important than accuracy.

P3. Wallace's Line

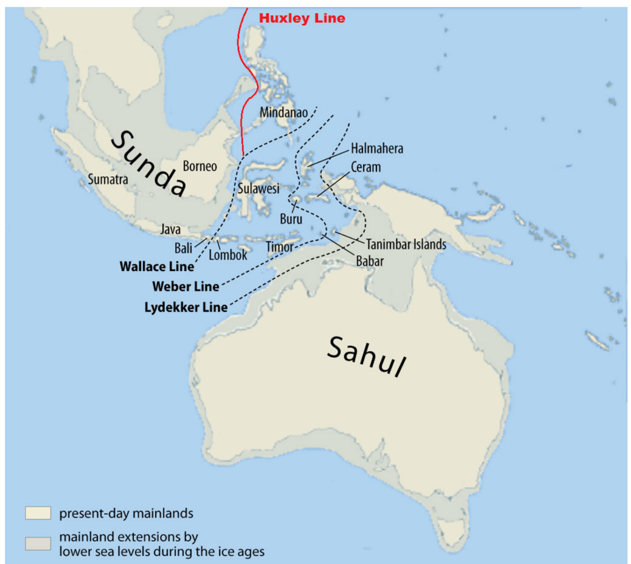


Figure 7.13: Wallace's Line

In the paper "Evolution, biogeography, and maps: An early history of Wallace's Line" [76], Camerini provides a focused account of historical details relating to Wallace and Darwin's efforts towards the development of the theory of evolution.

The point of the paper is that Wallace and Darwin were both able to develop essential parts of the theory of evolution only when they were able to literally see how different populations were spread out over different geographic areas. By examining information they already had in other forms and representing it visually on a map, they gained insights and saw patterns they could not see before.

Also, the accuracy of the actual position of the line did not matter very much, but putting a line on the map made a huge difference.

For my research, the take away from this example is that trying to employ visual tools with the intention of representing inherently non-visual information can have a powerful impact on one's understanding of the information, regardless of how accurate the representation is.

P4. Visual Representation

The following papers provide a basis for understanding how and why visual representations are useful in conveying complex information in more accessible ways.

The Kulvicki [77] paper "Knowing with images: Medium and message" talks about how visual representations allow us to intuitively encode all kinds information, and how the same information, encoded in non-visual terms, would be far more cumbersome and harder to understand.

In Sheredos's [78] article "Why do biologists use so many diagrams?", the authors argue that "diagrams have distinctive characteristics that make them effective mediums for communicating research findings, but they are even more impressive as tools for scientific reasoning." In the same resource, we find several accounts of a practice-based preference among biologists to use graphical representations of inherently quantitative content.

These papers, together with Wallace's line and many others trace a clear picture that visual representation of non-visual information is a powerful tool for scientists from diverse fields of study and even that without these tools, scientific discovery would progress at a slower pace.

P5. Misleading Visual Representations

A. Roskies in the paper "Are neuroimages like photographs of the brain?" [79] investigates the nature of the visual content of neuroimages and how that generated visual content differs from the actual structure of the brain:

> "Brain images are epistemically compelling, in part because they are likely to be viewed as akin to photographs of brain activity. [...] neuroimaging diverges from photography in ways that seriously undermine the photographic analogy [...][and] proper interpretation of brain images is much more complex than it appears."

The paper examines how fMRIs look like they are pictures of brain activity, but this is in fact deceiving. fMRIs track blood flow by amalgamating different kinds of statistical information and then generating something that looks like an image. By presenting this information visually, it is far easier for scientists to understand it. Yet, it is also potentially deceptive because it gives the incorrect impression that we are directly looking at visual or structure features of the brain when we are not (as opposed to looking at a statistical re-creation of certain neural properties given statistical software designed to look like an image).

There are two important ideas to take away from here. First, we build upon the already common theme that visual representations of information are easier to understand than other kinds of representations. Second, and most important, we need to be aware that synthetic visual information may naturally be confused with authentic visual information, which can be seriously misleading.

P6. Part Salience

The paper "Salience of visual parts" [80] is an excellent study of the process of making sense of objects visually, and particularly relative to the concepts of parts, boundaries, and salience.

The concept of minima rule is used in order to distinguish the fundamental parts needed for recognizing an object. By manipulating a fundamental part of the shape, we can also make a case for exhaustive content objects that appear obviously artificial in order to create a clue of virtuality.

7.3.7 Art Insights

The next section follows an eclectic list of insights ranging from sources such as journalism, literature, or cultural phenomena. We bundled them together under the umbrella term "art", for a lack of a better term.

A1. The Esemplastic Power of Imagination

In the midst of an epiphany about an overwhelming experience at the opera, Homer Simpson admitted, "you made me believe I was in a magical world where singing is talking" [81].

This subtle Simpsons moment is a mere glimpse into the breath-taking power of imagination. Following in Schopenhauer's footsteps, in *Biographia literaria* [82], Samuel Taylor Coleridge strives to amass the power of imagination's magnitude, substance and sublime nature, coining the term *esemplastic*[1] in the attempt:

> "The esemplastic power unifies, 'all in each', and arranges all ideas and expressions in one scale."

When exposed to a meaningful, gripping, and insightful experience one transcends one's limits, shatters the bounds of time, space and mind, and then steps into a world where veritable understanding is fluid and all-encompassing, where all is interconnected in wild, wily, and deeply profound ways.

A2. Emotional Impact

In one of the sketches [83] of the Drop the Dead Donkey show[2], a team of journalists was discussing the ethical implications of staging a scene by adding a teddy bear (Dimbles):

> "You know what these stories are like. You turn up, and the emergency services have cleared away all the carnage so you've got no pictures. And these are just creative touches to bring home the full drama of the story to the viewer. I've won three awards with Dimbles. All right, all right, I concede that maybe I've overused him a teensy bit.
>
> A teensy bit? This bear's visited more disaster scenes than Margaret Thatcher. It's the only cuddly toy to have taken part in the Iran Iraq War, where, as I recall, you claimed it was a mascot abandoned by martyrs of Allah."

The sketch itself was aimed at discussing the ethics of altering or doctoring a scene in journalism. The same scene without the teddy bear would affect the viewer psychologically in a completely different way.

[1] *Esemplastic*, a term first used by Samuel Taylor Coleridge and according to a memorable side note by Blob "and never used again since."

[2] Drop the Dead Donkey is a situation comedy that first aired on Channel 4 in the United Kingdom between 1990 and 1998. It is set in the offices of "GlobeLink News," a fictional TV news company.

The point we can take away from this story is that artfully-planted visual cues can have a powerful emotional impact while still being fundamentally irrelevant to the objective facts.

A3. Perception of Familiar Surroundings

Years ago, while working as a travel journalist in the Lofoten Islands in northern Norway, I met an old fisherman and he shared a few tales of the sea with me. There's one particular remark I recall vividly.

While comparing the roaring winter storms of the open waters of the North Atlantic to his native shores, he said that despite the fjords having stronger, unpredictable winds than the open ocean, as well as unforgiving currents and shoals that can wreck your ship in an instant, he is still much more at ease when, "he can rest his eye on a familiar mountain."

The phrasing, "to rest my eye on a familiar mountain," echoed profound emotional depths and I could see in his eyes the warm wood-fire of his Rorbu hut, the smell of fresh salmon, and in his smile I saw the laughter of his children running along the pier to welcome him back in the perpetual starry darkness of the polar night underneath a river of northern lights in all the colours of the rainbow.

From this story we can take away the insight that despite one situation being better than another as an objective evaluation of sailing conditions, one's emotional response may be counter-intuitive and dependent on cues such as a familiar sight or simply an action and/or an object associated with a certain desired psychological state (e.g. resting one's eye on a mountain).

A4. Guided vs. Exhaustive Content

A common-sense observation in improvisational theater is that trying to come up with content without directions is very difficult. If one is given a few clues to start from, then the imagination can take it from there and run free with the given scenario.

Our take on this theatrical technique is that a powerful experience is one where one's mind is taking an active part in creating content by filling in the gaps. We shall refer to this as guided content. Instead of experiencing an exhaustive description of something (i.e. exhaustive content), an experience based on incomplete content, guided by essential cues is a more human-friendly approach and better suited to create an organic experience.

One clear illustration that comes to mind regarding this conceptual dichotomy is the different experience of a story in the form of a book as opposed to a movie. From a visual perspective, the book is guided content, while the movie is exhaustive content.

7.4 Conceptual Principles

After exploring all of the insights at length, we can now move to the next part, the generation of conceptual principles.

By conceptual principles we understand a set of principles that determine the conceptual content pertaining to our solution. From a practical perspective, the difference between the insights and the conceptual principles is that while focused, the insights have no direct relation to the solution, they simply provide an explanation for some relevant aspect pertaining to the problem. The conceptual principles, on the other hand, are active in shaping the direction of the solution.

CP1. Transcendental Experience

The visual experience should address one's imagination as much as, if not more than it should provide information. One's imagination is where magical things happen, where a child sees the wind as clear as day, even when there are no senses to actually see the wind.

The content shall tell a story, it shall plant accurate cues and details here and there, so that the actual experience will happen in the viewer's imagination, where there are no limits to the profoundness of one's connection to *all in each*[1].

CP2. Environment Awareness

The captain needs to be aware of the status of various environmental aspects adjacent to one's ship. Among these aspects, the most important are the wind, the shore, and the tidal currents for coastal sailing. For off-shore sailing, the most important aspects are the wind and the atmospheric pressure. Also, for any kind of sailing, the captain needs to be aware of nearby ships, wildlife, and debris.

[1] "On the Imagination, or Esemplastic Power" Ch 13, Biographia literaria, STC. [82]

Code	Insight
S1	The captain, the vessel and the sea
S2	Data Sources
S3	Heeling Danger
S4	Electronics Malfunction
S5	First Mate
S6	Non-linear Perception
G1	Wind Estimation
G2	Motion Assessment
G3	Tidal Currents
V1	Rubber Duckies
V2	Representation Ambivalence
V3	Way-points
H1	Meta-Information
H2	Three Scenarios of AR
H3	Bird's Eye View
H4	To each Media, their own Representation
E1	Navigation/Planning Separation
E2	Seasickness Reduction
E3	Anxiety Reduction
P1	A Quest for Essence
P2	Representation Model Accuracy
P3	Wallace's Line
P4	Visual Representation
P5	Misleading Visual Representations
P6	Part Salience
A1	The Esemplastic Power of Imagination
A2	Emotional Impact
A3	Perception of Familiar Surroundings
A4	Guided vs. Exhaustive Content

Table 7.1: List of insights

CP3. Ship Awareness

The captain needs to be aware of the status of the ship's systems, most importantly propulsion and navigation equipment. Access needs to be provided in a reliable and immediate way to information relative to these systems. Wherever electronic sensors can be used, the data should be integrated into the sensing system. For aspects that cannot be accessed by any other means than one's senses (e.g. sail telltales), the electronic system should be designed to allow for a break in the captain's attention to attend to these aspects.

CP4. Centralized Data

Access to data should be centralized wherever possible, to speed up the access time. The solution should integrate data from as many sources as possible. It should also display it in as few places as possible.

CP5. Heeling Awareness

Strategies for preventing excessive heeling require understanding of the reasons why heeling happens. When the inexperienced sailor can't predict the potentially dangerous heeling in advance, our solution should perform the prediction instead and enhance heeling awareness.

CP6. Mission-Critical Design

The electronic system has to be designed according to mission-critical redundant principles. If there is a failure, it should be only local, without impacting the entire system. Instead of using a monolithic paradigm the system should mandate partial functionality for mission critical features.

CP7. Synthetic Synesthesia

Synesthesia in this context is used as an analogy, not literally. Understanding of geo-physical phenomena that cannot be natively assessed using human senses, should be represented visually (e.g. depth, atmospheric pressure, etc.) Information about the wind, tidal currents, and forward motion must be visually represented as closely as possible to what would be the actual sensory perception.

CP8. Pseudo-Natural Appearance

The appearance of virtual content featured in supporting AR roles should be pseudo-natural:

Natural. The content should be as close as possible in appearance and behaviour to its corresponding entity in real life.

Pseudo-. There should be one obvious and fundamental difference carefully planted so that the virtual content can never be mistaken for genuine scene content.

CP9. 4 Paradigms of Visualization

In strong contrast to existing navigational tools that mix all the visual content together, I conceptually classify the system entities using four different paradigms of visualization collected in the form of two fundamental dichotomies. The first dichotomy is based upon perspective and it identifies a detached versus an immersive experience. The second is based upon the level of abstraction of data and it identifies natural versus symbolic content representation.

CP10. Experience Awareness

The interface should be flexible enough to accommodate the needs of a broad spectrum of users. Despite trying to create a consistent experience, I should be aware that sailors may have different needs depending on their experience level. Sailor caught in a storm off-shore may want a reduction in the interface information to the bare essentials. Inexperienced captains in coastal waters may want exaggerated features to highlight and predict potential danger.

CP11. Course Awareness

The system should address the captain's need for course awareness by facilitating access to information regarding the desired course, the actual course made good, and the difference between them.

CP12. Representation Synergy

The various kinds of information to be displayed should be individually analyzed to determine the most appropriate graphical representation. The representations should tell a story and be intuitive regarding the subject they represent. More than one kind of representation for a certain subject is acceptable, where appropriate (e.g. pseudo-natural *and* abstract representations).

Ultimately, the information should be displayed in a form that is in harmony with everything: boat, environment, and the captain.

CP13. Blind-spot Awareness

The system should make captains aware of their blind-spots and also supply new insights. The captain's own existing knowledge should be respected and only new information should be added, without stating the obvious.

CP14. Emotional Stimulation

Visual cues can trigger wildly powerful emotional reactions. While objectivity is indeed important, carefully crafted little details that may seem insignificant to the scientific-oriented observation may make the difference between having a sterile image that speaks to the reasoning mind, or an organic image that informs while also serving as a ramp to inducing powerful emotional states. If we can, we should investigate the possibility of incorporating non-distracting, calming (familiar) visual cues in stressful sailing situations.

CP15. Goldilocks Scenario

The scientific models behind the data acquisition process should try to reach a balance between too detailed or too abstract.

For a complete list of the conceptual principles and their dependencies, see Table 7.2.

7.5 Design Principles

In this section I will discuss the design principles I identified. The difference between the conceptual principles and the design principles [84] is that the former deal with more general, abstract concepts, while the latter are focused on providing more specific, practical constraints and hints.

Ultimately, both sets of principles are used to derive a set of system features, as we will see in the next section.

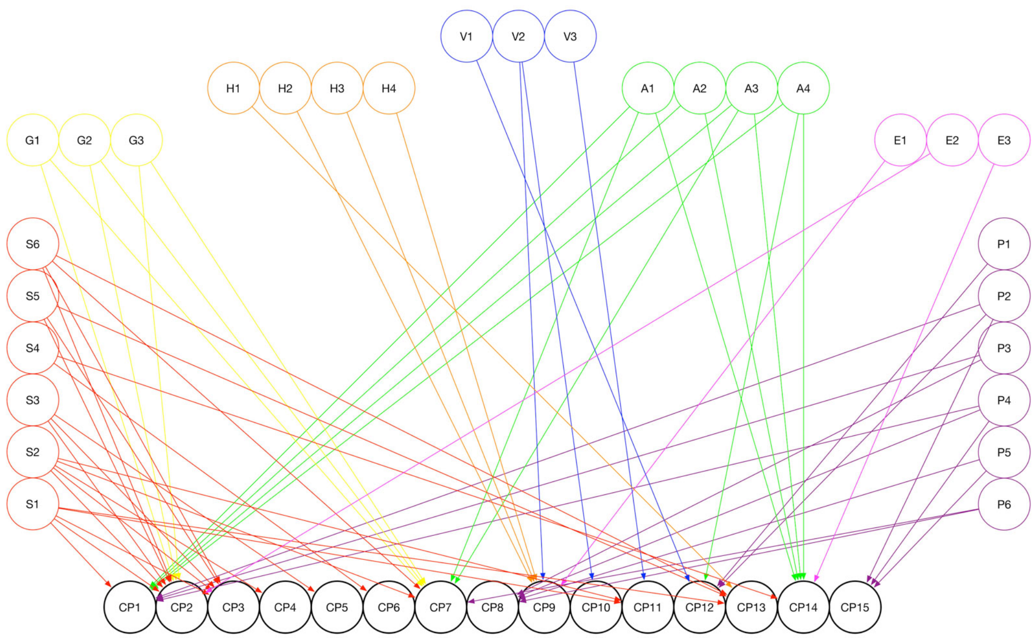


Figure 7.14: Conceptual flow between insights and conceptual principles. See Tables 7.1 and 7.2 for a list of symbols

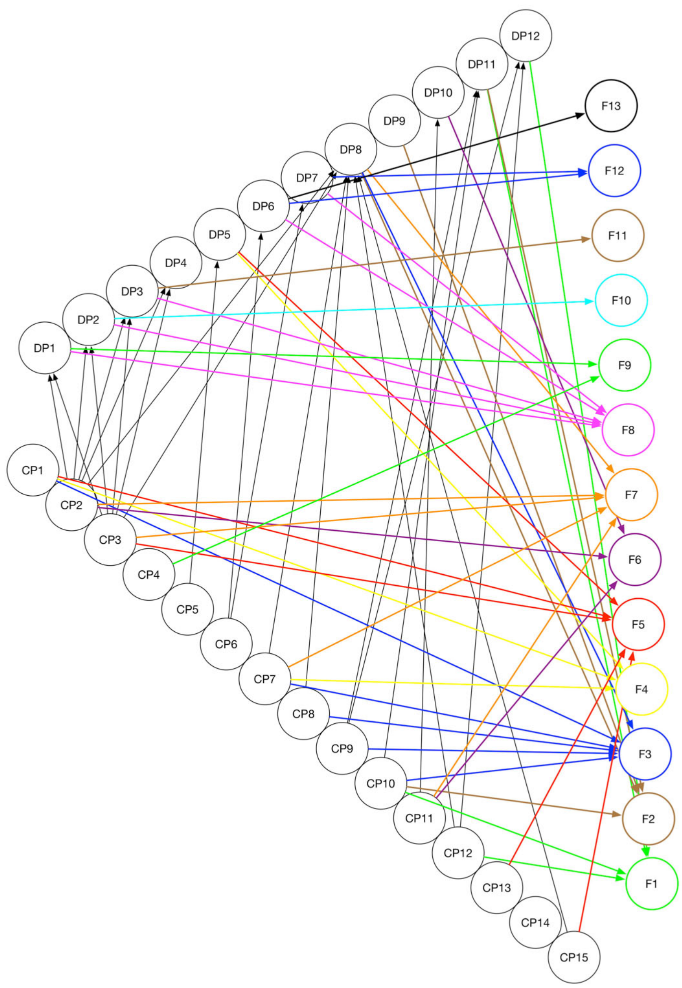


Figure 7.15: Conceptual flow between conceptual principles, design principles and features. See Tables 7.3 and 7.2 for a list of symbols.

Code	Conceptual Principle	Based on
CP1	Transcendental Experience	A1-4, P2-4, S1
CP2	Environment Awareness	E2, G1-3, S1-3, 5, 6
CP3	Ship Awareness	S1-3,5,6
CP4	Centralized Data	S2
CP5	Heeling Awareness	S3
CP6	Mission-Critical Design	S4
CP7	Synthetic Synesthesia	A1,3, G1-3, S2, S6
CP8	Pseudo-Natural Appearance	P3-6
CP9	4 Paradigms of Visualization	H1-4, E1, V2
CP10	Experience Awareness	V2
CP11	Course Awareness	S1,2, V3
CP12	Representation Synergy	A4, P1,2, V1
CP13	Blind-spot Awareness	S1, S5,6, H1
CP14	Emotional Stimulation	A1-4, E3, S5
CP15	Goldilocks Scenario	P2,4,5

Table 7.2: List of conceptual principles

DP1. Instruments Interface

The system should interface existing boat instruments (e.g. anemometer, depth sounder, impeller log, GPS, etc.)

DP2. Enhanced Sensing Capabilities

The system should provide sensors for data sources that are absent among the native vessel instruments (e.g. camera, accelerometer, gyro, magnetometer, hygrometer, barometer, etc.)

DP3. Display Device(s)

The provided information should be presented on one or more display device(s) (e.g. tablet, phone, AR glasses, indoor monitor, external screen, etc.)

DP4. Visual Interface

The display device(s) will feature a graphical user interface, where the screen space will be comprised of an amalgamation of visualization areas.

DP5. Visualize Heeling

The heeling tendencies of the boat should be analyzed and dangerous heeling should be forecasted and visualized. Our solution should provide a visual warning about dangerous heeling either while it is happening or, preferably, ahead of time.

DP6. Distributed Topology

Following a modular design, where individual units are isolated and specialized to a certain functionality, the system should feature a distributed topology. The individual modules should transfer data wirelessly as much as possible.

DP7. Electric Shock Protection

The individual electronic system components should maintain functionality despite the potential of an electric shock in the system (e.g. lightning strike, reverse polarity, etc).

DP8. Supporting Visual Cues

In the pseudo-natural paradigm, the wind, current, and boat motion should be visualized using supporting visual cues featuring pseudo-natural content.

DP9. Scene Modelling

The AR scene should be customizable in more than just appearance, in componence[2]and ultimately in essence. For this purpose, no explicit (hard-coded) scene should be used, but instead the scene should be generated from a conceptual description of the media that inhabit it.

DP10. Route Integration

The system should provide a feature that can import way-points from planning software. Both the desired route (from way-points), and the actual course made good should be available, as well as potentially highlighting the difference between the two.

[2] *componence* - (linguistics) The composition of a grammatical structure in terms of the components it contains, without regard to their arrangement.

DP11. Display Areas

The display should represent distinct layers or areas. The main area layer (i.e. the background) covers the entire display and it displays the live video feed from the camera. Additional immersive layers featuring pseudo-natural content (e.g. wind/current particle cloud, visual cues etc.) also cover the entire display. Other areas include a bird's eye view dedicated to the visualization of more abstract information (e.g. vector composition for current calculation).

DP12. Mix and Match Content

Just because the immersive area is typically associated with pseudo-natural content and the bird's eye view area is associated with more abstract representations, it does not mean they cannot feature any kind of available content. An arrow-based representation of the current may be used in the immersive area or a particle cloud-based representation of the current can be used in the bird's eye view area.

For a complete list of the design principles and their dependencies, see Table 7.3.

Code	Design Principle	Based on
DP1	Instruments Integration	CP2,3
DP2	Additional Sensors	CP2,3
DP3	Display Device(s)	CP2,3
DP4	Visual Interface	CP2,3
DP5	Visualize Heeling	CP5
DP6	Distributed Topology	CP6
DP7	Electric Shock Protection	CP6
DP8	Supporting Visual Cues	CP2,3,7,8,12,15
DP9	Scene Modelling	CP9,10
DP10	Route Integration	CP11
DP11	Display Areas	CP9,14
DP12	Mix and Match Content	CP9,12

Table 7.3: List of design principles

7.6 Distinctive Features

In this section I finally arrived at the core of my research, the distinctive features of the system. I use the word feature as having the meaning of a description of a particular characteristic of the system, and not as the more widely used meaning of implementation. Extensive implementation details of the features can be found in form of system specifications, in Chapters 5 and 6.

Even more specifically, in this section I will look at the *distinctive features*, meaning of features that set our implementation apart from other, commonly used instances of corresponding entities in related fields of study. For example, most of the electronic components of my system are interconnected using Websocket technology, based on a TCP/IP network; this would indeed be a feature of the system, but since the use of this technology is considered to be widespread and an obvious choice, I simply assume it, without mentioning it as being a distinctive feature.

In order to paint a clear picture of the system, I encourage the reader to start off from the list of distinctive features and, where details are not provided, to fill in the gaps using the most obvious solutions according to current technological trends.

First of all, I need to clarify the explicit meaning of a few terms: by *screen* I mean the working area that can be used by my software to exhibit visual content. The related term *display (noun)* covers the hardware aspects of the visualization process (i.e. the display is 4 inches wide and made of plastic). As an action, *to display (verb)* is used for both software and hardware with the widely accepted meaning.

F1. Customizable Screen Areas

The screen is composed of three different kinds of areas:

1. **Main area.** Forms the background of the visualization; it features a live video stream and additional overlayed virtual content (Section 6.2.1)

2. **Picture-in-picture area.** Smaller area, blends into the main area (Section 6.2.2)

3. **Panel area.** Windows with specialized content (numeric, graphs, menu etc.) (Section 6.2.3)

F2. Customizable Perspective

In the main and PIP areas, the perspective of the scene/content can be customized:

1. **Immersive perspective.** The content is synchronized with the video feed and is distributed around the viewer (Section 6.3.1)
2. **Diorama perspective.** The boat is seen from a bird's eye view perspective and the content is displayed around the boat (Section 6.3.2)

F3. Customizable Content Appearance

The appearance of the visual content presented to the sailor can be categorized according the following taxonomy:

1. Non-spatial representation
   (a) **Numeric content.** Quantitative information like heading or depth (Section 6.4.1)
   (b) **Graph content.** Graphs that provide information about the tendency of various readings, like depth (Section 6.4.2)
2. Spatial representation
   (a) **Natural content** Visual content streamed directly from the cameras (Section 6.4.3)
   (b) **Abstract content** Abstract visual content such as vector arrows, grid, distance rings etc. (Section 6.4.4)
   (c) **Pseudo-natural content** Visual content that comes in pseudo-natural form, such as particle clouds, 3D models etc. (Section 6.4.5)

F4. Pseudo-natural Appearance

The pseudo-natural content can be explained as content that first looks natural (most of its characteristics follow a natural appearance), and second there is a significant characteristic that makes it stand out as obviously virtual content, so it cannot be mistaken for natural content. (Section 7.4, section 6.4.5).

F5. Distorted Content

One method for achieving pseudo-natural appearance for content is by exaggerating features, like a warped grid, or an unnatural colour in bio-luminescence (Section 6.4.6). Distorted content, like exaggerated heeling angles, could be also used to alert sailors to danger.

F6. Way-points

The system has a feature for importing way-points and displaying only the ones that enter a local horizon (e.g. approx. 0.1nm)

F7. Visual Elements

The visualization component of the scene employs several visual elements to illustrate the following characteristics:

- ☐ Heading
- ☐ Course
- ☐ Motion
- ☐ Orientation
- ☐ Wind
- ☐ Tidal current
- ☐ Depth
- ☐ Way-points

F8. Decentralized System

A system (Chapter 5) distributed over a boat network featuring sensing, processing, and visualization modules. The system is decentralized, as opposed to the monolithic paradigm used in most common marine devices (e.g. GPS chart-plotter, radar etc.), allowing for failures to be localized, rather than catastrophic.

F9. Instruments Interface

The sensing module (Section 5.2) has a unit dedicated to interfacing existing boat instruments (Section 5.2.3). Among the interfaced instruments are an anemometer, GPS chart-plotter, impeller log and others.

F10. Telemetry and Internal Units

Other important sensing capabilities are provided by the telemetry unit and internal units. The telemetry unit provides data regarding boat position, orientation, motion, and others (Section 5.2.1). The internal unit provides data regarding battery level, tank levels, temperature and humidity (Section 5.2.4).

F11. Visualization Broadcast

The visual content (Chapter 6) is provided to users via any device that can access the boat's WiFi and can support a JavaScript and WebGL-capable browser. Some of the devices I tested include laptops, tablets, and smartphones (Section 5.5).

F12. Inductive Charging

The processing server, telemetry, internal, and imaging units provide wireless data and they are powered through their own batteries, charged via inductive charging. This prevents the risk of catastrophic failure due to a short circuit as a consequence of unforeseen factors in the electrical system (e.g. lightning strike, alternator failure, etc.)

F13. Server

The boat server acts as the main processing, logging, broadcasting agent, having two main tasks: to accumulate real-time data from the sensors and to provide visualization content (Section 5.4).

Among the processing tasks, some of the most significant are data filtering and information modelling (abstraction). The processing unit can be doubled with a backup unit, running in redundancy mode.

For a complete list of the features and their dependencies, see Table 7.4.

7.7 Conceptual Flow

After identifying and delving into all the concepts I covered, I will formalize the relationship among them.

The use of the following complex web of conceptual inter-connectivity aims to provide a central core for our symbolic representation of the entities

Code	Feature	Based on
F1	Customizable Screen Areas	CP10,12,14, DP11,12
F2	Customizable Perspective	CP10, DP8,9,11
F3	Customizable Content	CP1,7,8,9,10,DP8
F4	Pseudo-natural Appearance	CP1,7,DP5
F5	Distorted Content	CP1,3,13,14,DP5
F6	Waypoints	CP2,11,DP10
F7	Visual Elements	CP2,3,7,11,DP8
F8	Decentralized System	DP1-3,6,7
F9	Instruments Interface	CP4,DP1
F10	Telemetry and Internal Units	DP2
F11	Visualization Broadcast	DP3
F12	Inductive Charging	DP6,7
F13	Server	DP6

Table 7.4: List of features

and considerations at play and to lighten the Atlassian burden of holding all of them up in the air, while trying to make sense of how to make use of them [85].

In the previous sections we encountered four tables: 7.1, 7.2, 7.3 and 7.4, that recounted insights, conceptual and design principles and features, respectively.

In these tables we see that a certain entity has a code, a name, and is based on another entity (or none for insights). Is we start parsing the features using the "based on" information recursively, we end up tracing all of the conceptual relations, all the way to insights.

Using a flow graph, I track the conceptual relationships between the considerations that played a role in the emergence of the features:

- ☐ To trace the bottom up emergence of features by slowly bubbling from hard facts and observations to abstract representations (i.e. insights and principles), that are ultimately crystallized into a hardware/software feature shaped by a clearly stated purpose, which satisfies a contextual necessity (Figure 7.16).

- ☐ To split apart the manifold of existence into varying conceptual realms as part of a local horizon of relevance.

☐ To examine the entities and processes that inhabit these conceptual realms and to create an abstract model of understanding regarding their underlying essence.

☐ To form a vision of the sailor's needs in terms of a visual experience.

☐ To build an esemplastic augmented reality scene that finds an appropriate place for each visual element, where they can transcend their medium and germinate in harmony with the sailors' imaginations.

☐ To investigate the process of data-gathering and to reformulate it in a way that can be visually delivered to sailors.

☐ To facilitate an immersive, meaningful, transcendental visual experience that caters to the imagination and delivers immediately useful visual content.

7.8 Summary

In this chapter I create a record of the design process by modelling the interdependency between all of the conceptual elements that played a role in drafting the solution in its current form.

In Chapter 4 we saw a similar process through which I found the shape of our solution. In this chapter I continued the previous work and filled in the details by starting from a collection of observations; then through a process of ideation, found a set of insights, organized into six categories. Then, from these insights, a set of principles emerged. These conceptual and design principles guided me towards a brief set of feature descriptions that specified the system components.

Lastly, I tracked all of the elements using relational tables of entities and created a visual, graph-based representation of the conceptual relationships.

This chapter offered an investigation of the research problem as well as facilitated the leap towards a detailed solution with features and specifications.

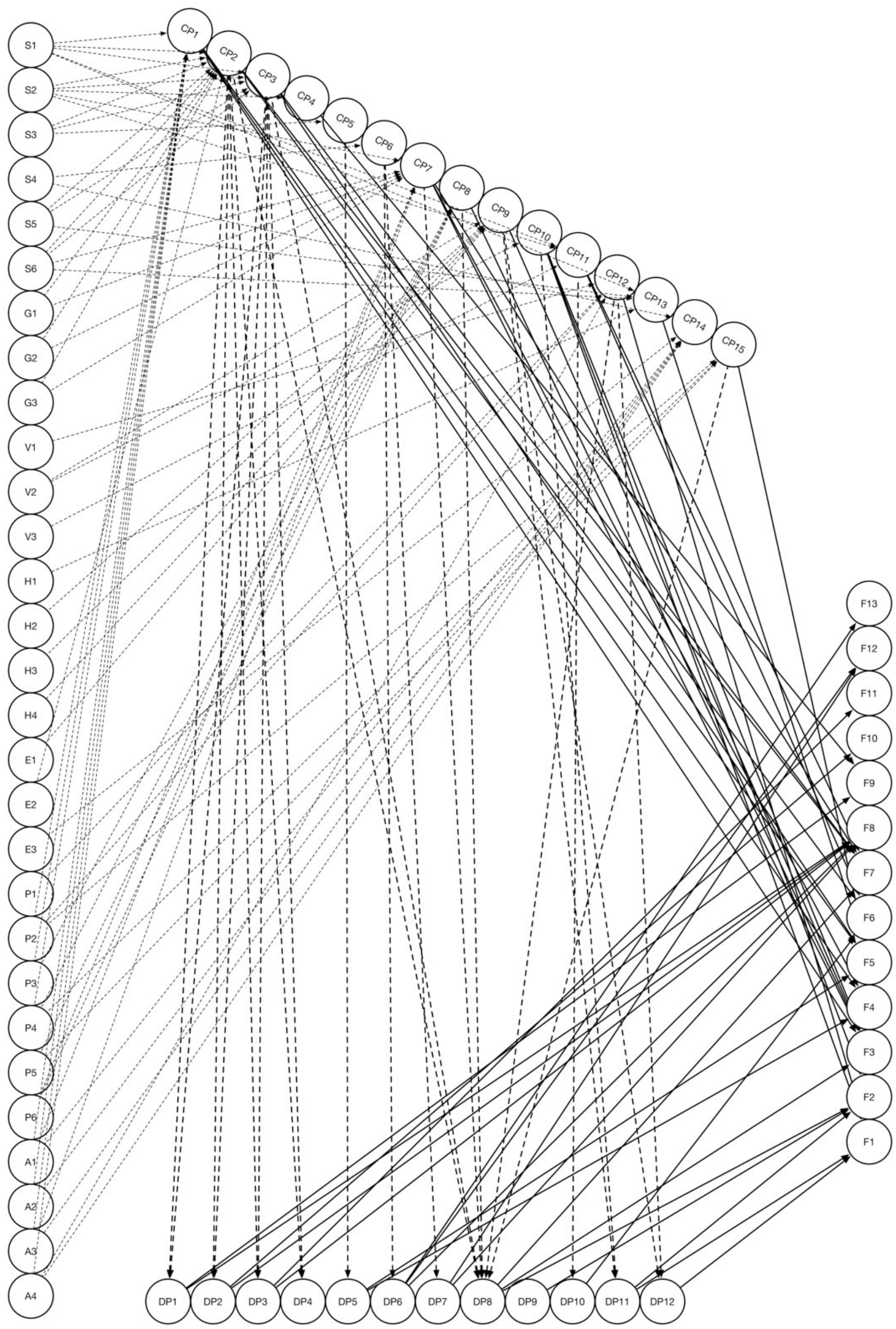


Figure 7.16: Conceptual flow between insights, conceptual principles, design principles and features. See Tables 7.1, 7.3, 7.2 and 7.4 for a list of symbols.

Chapter 8

Future Work

8.1 Model Sailboat

There are obvious limitations in the process of developing and testing navigational sailing equipment. Due to the improvised nature of prototypes designed for research purposes, the trustworthiness and reliability of the equipment is significantly less than established, off-the-shelf products. Fortunately, most of the equipment I have used so far is relatively small in dimensions and can easily be mounted on a 13 ft model of a sailboat, instead of the 23, 26, and 35 ft sailboats normally used. The system is designed to broadcast the information feed over a network. As a result, operators don't necessarily have to be in the boat; they can be on the shore, receiving data, rendering the AR scene locally, and transmitting commands back to the model ship over a remote control.

Recent research in the field of sailboat automation [86] shows promising results using a free-rotating wing sail. Such a setup is made up of a rig that requires only one linear actuator for the sail and another linear actuator for the rudder.

In the future, I hope to either retrofit an existing 2.4 mr sailboat to a wing-sail or to establish a partnership with an existing research project to deploy my AR visualization technology to it.

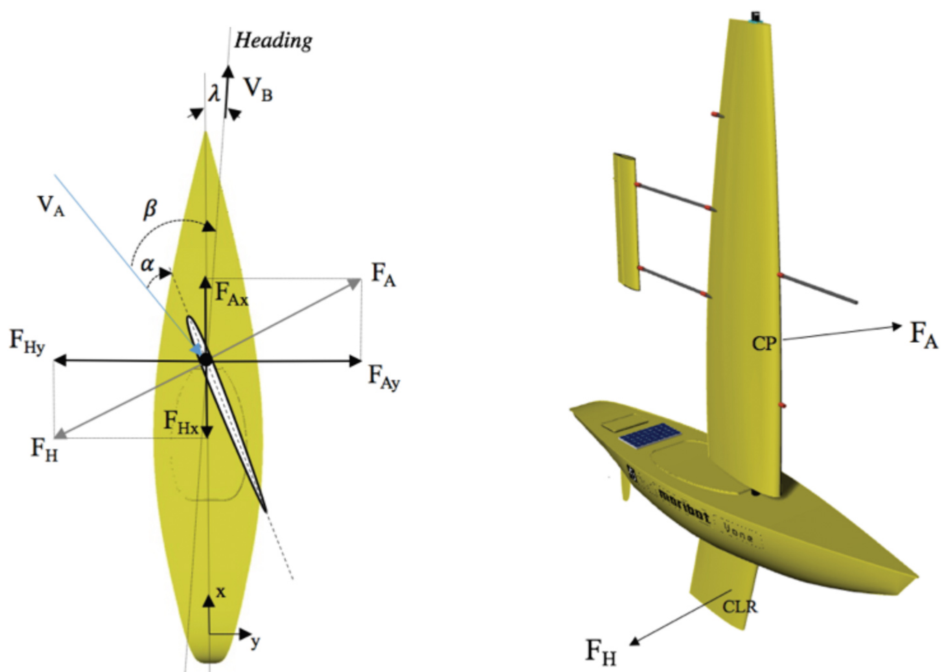


Figure 8.1: maribot Vane wing-sail sailboat model

8.2 Remote Sailing Training

Another direction my research could go into is remote teaching and in particular instructional applications. By implementing the ship's system as an IoT device, sailing instructors could sit in an office in Victoria, while their clients would be sailing in the Bahamas. The sailing lesson would take place over a significant distance, but it would take place nonetheless.

8.3 Extended Implicit Modelling

We have barely scratched the surface of the potential for the paradigm of implicit modelling. At the moment, I am aware of past and present efforts to use implicit modelling for shape generation, but I have attempted little beyond the scope of geometric shapes.

In broad terms, implicit shape modelling approaches the problem of generating a shape based on a mathematical description involving the sampling of a field generated based on a set of geometric primitives and operations. There are several other interesting proposed methods of generating shapes based on parametric descriptions, among which attribute-based modelling comes to mind and would be an alternate candidate for AR scene modelling. For my purposes, however, I focus on the concept of fields radiating from primitives, permeating space.

Implicit material modelling picks up a shape and uses a mathematical/physical/chemical description to generate a distribution of matter inside the shape; properties such as density, colour, or even chemical substance can be modelled throughout the given shape.

Implicit scene modelling generates an augmented reality scene (i.e. similar to a theater stage) with distinct entities interacting with one another, based on an ontological description of the real-world model for the generated content.

In the following sections we have included implicit shape modelling and implicit material modelling for the purpose of providing a stepping stone towards implicit scene modelling.My preferred method of investigation is that of extending the reader's understanding of a certain topic by introducing new content in a step-by-step fashion using analogies to known topics.

8.3.1 Implicit Shape Modelling

The field of implicit geometric modelling is complex and there are several decades of research that went into the investigation of the process of generating shapes based on a process of sampling geometrical primitive-derived fields.

An early paper on the topic describes these generated shapes as, "a surface of constant value in a scalar field over three dimensions." [87] The complexity of the shapes can be enhanced by using advanced techniques, such as sketch-based modelling with BlobTrees. Using such an approach, "sketch-based modelling operations are defined that combine [...] basic shapes using standard blending and CSG operators." [88]

There are countless resources that approach the various facets of implicit geometric modelling, but for my conceptual purposes, let's settle on a few fundamental terms:

- ☐ Primitive - a geometric shape with a known position and orientation in space.
- ☐ Field - the space adjacent to a primitive that extends and permeates the surrounding space.
- ☐ Sampling value - A certain value at which the field around a primitive is sampled.
- ☐ Operation - a technique that combines primitives and/or fields to generate desired shapes using a system of operators.

8.3.2 Implicit Material Modelling

In the traditional sense, the point of implicit modelling is to create shapes using geometric operations through primitives and fields that permeate space. This kind of representation is suitable for the process of computer rendering, where shapes are immaterial. Textures can be used to imitate material properties, but are ultimately still immaterial.

In implicit material modelling I look closely at additional properties that augment a given shape. For this purpose, I can explore the vision that the primitives and fields contained in space are only one layer of many.

Shape is a most obvious object property and it is an excellent place to start; I shall call this Layer 1.

When I consider objects in the real world, however they consist of matter and therefore have material properties, like density, colour, or chemical substance.

Since rendering only approaches immaterial content, I need to look at different processes to see potential applications, with the most obvious one being 3D printing. For 3D printing, density is an important property to consider.

Let's assume I have a simple pill-like shape and I want to distribute a known volume of plastic throughout the shape. I could use current 3D printing techniques and allow an algorithm to distribute the plastic according to a strategy, usually concatenating layers with hexagonal or other shapes, like we find in a honey-comb.

I propose envisioning a density layer (Layer 2) with its own field, a density field based on density primitives (i.e. unrelated to the shape primitives). I could distribute the plastic homogeneously by assigning a constant value (e.g. 1) in the density field for the entire space it occupies. When I 3D print this configuration, I would see a completely full shape with no gaps inside.

Now let's suppose I use a step function over the density field. Everything on the left side of the axis of the pill is 1 and everything on the right side is 0. The shape of the pill remains untouched, but the material density is 1 on the left and 0 on the right. When I 3D print, I get half a pill.

If I reduce the density value from 1 to 0.95 and 3d print again, I would see air pockets start to appear randomly because the individual blobs of plastic would solidify in random shapes in the closest position to where it was injected.

Next, let's use a grid and sample the density field at various points where the shape meets the grid. Let's assume that the grid will match the printing resolution of the 3D printer. So, now I can create a density gradient, going from the leftmost point on the pill to the rightmost with values ranging from 0.25 to 0.75, respectively. Plastic is ideal because it can stretch a volume of material over a shorter or longer distance to match our density specifications.

There is great freedom in generating structures based on the density field simply by combining the grid points in different ways. I can slice it and create sequential 2D structures. I can sample it by grid point adjacency and create skeletal tetrahedral structures. Or if I were to print in graphite, I could use planar structures with varying orientations.

Using similar methods to CSG, I can distribute density to create the material equivalent of a peanut shell, hollow on the inside and with a particular material distribution throughout the shell.

Seeing what I can do with density alone, let's consider more potential layers. Colour is a material property that can be modelled based on colour primitives, fields, and operators. Chemical composition is another one. Printing in 3D with soluble and insoluble substances offers great shape freedom and solves the problem of printing supports to prevent sagging.

The most important point we are trying to make, however, is that shape is only the beginning, and that object properties can be modelled using fields and primitives as part of a layered model.

8.3.3 Implicit Scene Modelling

In the previous two sections, I talked about implicit modelling from the perspective of modelling objects by controlling shape and material properties, respectively. I did so in order to create a conceptual stage against which I could introduce our proposal for an implicit modelling approach to scene generation.

Our augmented reality stage will be designed to fulfill the purpose of compiling virtual content to be attached to video content captured in the real world.

I have already encountered the most common scene entities in Chapter 6.

In section 8.3.1 I worked with one layer comprised of a scalar field to generate the shape of an object.

In the following section, 8.3.2, I started adding subsequent layers comprised of their own scalar fields to add material properties (e.g. density, colour, substance) to a given shape.

For the purpose of creating an AR scene using the same multi-layered paradigm as used before, I propose a dichotomy of understanding and representation between the real-world and our virtual content.

The real-world experience as captured by a video device is a sampling of the manifold of localized existence. The captured video content, however is only a recount of the elements that fit within the limits of the capturing device. A video camera cannot capture the smell of a meadow or the strength of the wind. But, if we had a thermal camera, we could see the temperature of the elements in the scene.

I am trying to add information onto the visible spectrum captured video stream by synchronizing virtual content with the video feed. Some layers will be represented by scalar fields (e.g. temperature, atmospheric pressure, depth, etc.), while other will use vector fields (e.g. wind, current, boat heel, etc.)

The current model used for describing the scene elements and populating the scene is explicit. Scene elements like wind particles or debris on the surface on the water are predetermined to occupy a certain partition of the scene space, in which they are animated using real-time data.

My proposal for a future research direction is to establish an implicit system that would create a higher level of abstraction to describe the location of various scene elements based on the type of their underlying ontological nature.

For example, both the particles used for the wind and the objects used as debris on the water are particle clouds. The wind particles occupy the 3D shape described by a cuboid. The debris particles occupy a 2D shape space described by a plane that also coincides with the internal system representation of the idealized surface of the water.

Both the wind particles and the debris particles are implementations of a proposed type of scene primitives, particle cloud. The scene primitive particle cloud has a relation to shape primitives (see 8.3.1) as well as to material primitives (see 8.3.2). The material primitives would not be used and do not encode information literally, as in Implicit Material Modelling, but instead they determine how the AR scene is rendered. If I look at the way I try to visualize the wind, I see that the abstract particle cloud gets instantiated as inhabiting a certain cuboid, and that the particles will be based on maple leafs: i.e. they have the mass, appearance and behaviour of a maple leaf.

There is still a long way to go in this direction of Implicit Scene Modelling for AR purposes, and I hope I will see interest in the field in the future.

Chapter 9

Conclusion

There are significant efforts towards researching AR-based marine navigational awareness solutions, and there is an undeniable overlap between these and our solution. This overlap is mostly inherited from the use of an AR paradigm: perspectives, interface elements, registered content, etc.

There are, however, important differences: while most of the competing research efforts focus on optimizing the visual appearance and position of various elements as part of an interface [37], our research focuses more on a conceptual analysis and exploration of the nature, quality, and purpose of the content being displayed, while also attempting to find a close match between the visual and conceptual content of the AR scene.

The jump from a 2D environment to an AR paradigm can be seen in Raymarine's ClearCruise AR product [89], as well as other research projects (see Chapter 2). The information that is now being displayed using an AR perspective is almost exactly the same information that the chart-plotter uses in the 2D view mode. It's still numbers, arrows, and windows all the way, but this time overlayed on a live video feed from a camera. This kind of incipient obvious transition into AR is a natural development. Since most of the competing solutions are targeted at commercial shipping, it makes sense to take a gradual approach which doesn't alienate existing users.

We, on the other hand, have focused on sailboat operation, which has different priorities.

- □ **Propulsion.** A sailboat is propelled using sails; this means that the interface features a strong focus on visual aids to understanding the behaviour of the wind and tidal currents.

- ☐ **Dangers.** A sailboat, when compared to powerboats, faces different challenges and dangers (e.g. excessive heeling and restricted manoeuvrability); the interface provides information about these dangers in real time.
- ☐ **Visual experience.** Our interface includes visual features that provide information in a natural style, without the need to resort to numerical or abstract representations.

Since this is one of the first research projects earmarked for sailboat operation visualization, I undertook a thorough investigation of the underlying problem. I also had the luxury of starting from scratch and not being restricted by existing tradition or inertia. It is this freedom to innovate that allowed me to experiment with different electronic, conceptual, and visual components in my system. Most notably, I feel that the pseudo-natural appearance as well as the use of particle clouds and distorted content stand out against the general contemporary tendency of marine visualization research.

9.1 Contributions

9.1.1 Sailboat Control Scenarios

[C10] I conducted an in-depth analysis of the particular elements that comprise feedback loops in the process of sailboat operation, in three different scenarios (Chapter 3). These scenarios are idealized and exaggerated in order to support my assumption that implementing an AR visual interface is feasible. In reality, there are endless scenarios in the spectrum that meets particular vessel-control needs.

9.1.2 Preliminary Designs

[C11] I created a recount of the three design phases (or iterations) my project went through (Chapter 4). First I pursued sailboat automation, followed by semi-autonomous sailboat control, and finally settled on marine AR visualization. The chapter is presented from a design perspective, within a chronological/conceptual progression.

9.1.3 Sailboat Visualization System

[C1] I developed a vehicular visualization system featuring a network of devices, instrument interfaces, imaging capabilities, sensor readings, processing and broadcasting capabilities (Chapter 5). As part of the system, [C2] the telemetry and internal units feature an array of sensors not commonly present on sailboats (Sections 5.2.1, 5.2.4). [C3] The system also supports an immersive AR interface (Section 5.5).

9.1.4 Augmented Reality Interface

[C4] I designed an AR interface featuring a scene made up of entities that correlate with geo-physical phenomena that form the sailing environment (Chapter 6). [C7] I discuss the nature of these entities and of suitable potential visualization approaches (Chapter 6). [C12] I classified the different potential layers of abstraction for sailing phenomena (Section 6.4) and later [C13] discussed the prospect of using visual aids to achieve contextual visual awareness (Sections 6.4.5, 6.4.6).

9.1.5 Systematic Background Investigation

[C8] I devised a systematic approach to investigating entities and aspects vital to the process of sailing (Sections 7.3.1, 7.3.2). [C5] This approach was inspired by design-thinking and follows a conceptual flow that starts with observations that are used to gather insights. Next I see the emergence of conceptual and design principles that lead to features and ultimately system specifications. [C6] I created an interaction/correlation model for these entities (Section 7.7), by building a [C9] graph-based flow matrix that keeps track of the extensive number of inter-dependencies among observations, insights, principles, and features (Section 7.7)

9.2 Limitations

The research project in this dissertation can be aptly described by terms such as interdisciplinary or composite. Its scope spans a vast spectrum of knowledge, starting with practical aspects like sailing, soldering electronics boards, or building mechanical implements. Then, it ventures into more technical aspects like data sampling, information processing, PID configurations, frame interpolation for animation, etc. Next, I derive theoretical aspects from topics like design-thinking, philosophy, and cognitive science. And last, I deal with implementation aspects like running wires, configuring a network, writing thousands of lines of code, and drawing up an AR 3D visual scene.

I used existing resources to the extent possible. I adopted ideas from recent research in many areas. I, however, had to break new ground in many areas, too. I evaluated many of the features I created from an autobiographical perspective to speed up the general system development.

I am aware that user studies on various aspects presented here would be of great advantage and I am planning to undertake several user studies in future projects.

Appendix A. Sea-trial Report

This document is a recount of the findings collected during the sea trial dated May 16, 2015.

During the sea trial, I exhaustively documented the sequence of tasks needed to prepare the vessel, launch it, sail for a routine stretch, round a dangerous day-marker under sail, and safely return home.

The sea conditions were fair, however the southwesterly wind was relatively strong, ranging between 10 and 20 knots, with strong gusts being influenced by various shore and land features. Under these conditions, the skipper had to devote a significant amount of attention to the operation of the vessel as high speeds (4-7 kn) were commonplace. At these speeds, only an experienced skipper can cope with the vast amount of prediction that needs to be calculated, both in terms of forecasting the behaviour of the environment as well as the behaviour of the vessel.

The route I chose started and ended in Cadboro Bay at the Royal Victoria Yacht Club. After successfully hoisting the sails, the route followed the shoreline south, in the direction of Oak Bay. Just before Cattle Point, in Flotsam Cove, the skipper was asked to ignore the marine safety warning signs and round a day-marker on the danger side while under sail.

Please see Figure 1 for more details about the recorded route.

I did this at high tide, allowing for a clearance of at least 2m under the keel and a distance of about 10m between the day-marker and the closest shore feature. This task was chosen as a deliberately difficult manoeuvre to test the attention span of the skipper and to push him to his limits.

During the sea trial, I used a voice recorder to capture a detailed description of the tasks as I performed them.

In the Observation section, I recorded several observations and notes.

The subsequent Transcript section is a literal, detailed recount of the voice recording.

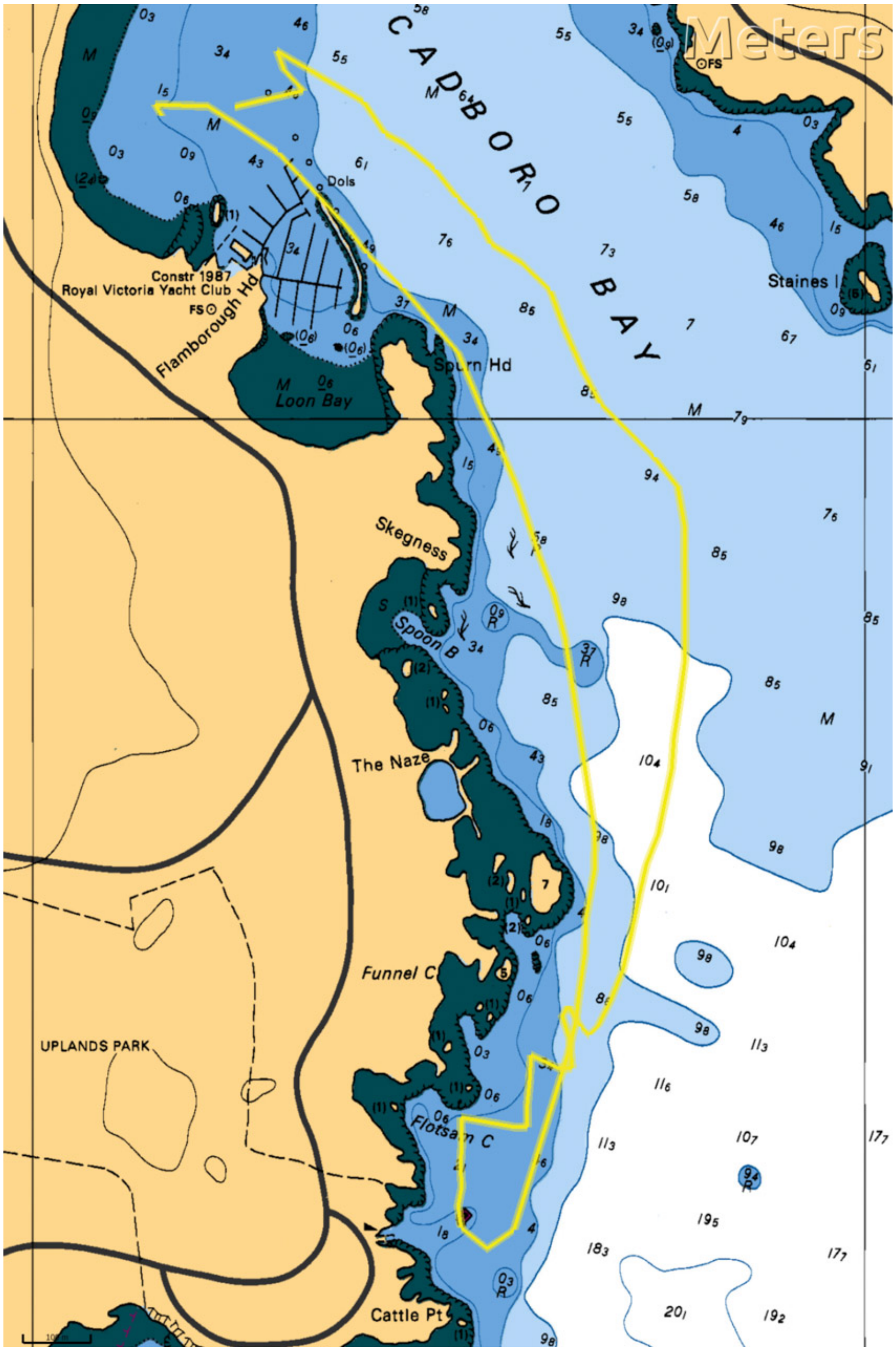


Figure 1: Sea Trial Route May 16

Even though the original recording intermingled the tasks and observations, I split these into their respective sections, for clarity.

.1 Observations

In this section, I recorded the notes and observations I made during the test trials. Because I wanted to capture not only the content, but also the general feeling of the moment, I kept the following observations unaltered.

> "If I had a wind instrument, I would know where the wind is coming from without having to look up at the top of the mast all the time."
>
> "I am inspecting the shape of the sails anyway, so checking up on the wind indicator is convenient."
>
> "The GPS [chart-plotter] is an advantage; it helps me have an idea about where I am on the map [relative to the shore]."
>
> "On a small boat, a depth sounder is very important, especially around familiar shores."
>
> "It's hard to control the boat while winching. An autopilot would be a great advantage. [...] I have to decide whether to continue trimming the jib or to steer."
>
> "One hand on the tiller, another one on a line, I have to let go of the tiller to do the winch."
>
> "I can only look at the chart for 1-2 seconds, things are happening very fast."
>
> "Checking the wind, sails, water, current, steering and everything else is all automatic. I'm aware only of the planning process for the rounding strategy."
>
> "I'm picking a range to visually determine the motion."
>
> "I'm preparing the tack: I'm looking at the windward sheet, at the leeward sheet, grab the handle, helm's alee."
>
> "I don't have time to look at the GPS, I'm only monitoring the depth while getting ready to tack."

"From the winching position, I can't see the wind indicator. I see the sails, but I'm guessing the wind direction."

"While heeling over 20deg, it would be great to see the wind."

"I see a sailboat going very fast against the background of Chatham Island, which makes me think there's a strong current there."

"Not enough time to do important tasks and I chose them by how urgent they were while guessing a lot."

"I left the tiller unattended, even when it was steering in the wrong direction because I was trimming the jib. It was more important."

.2 Transcript

This section represents a recount of the voice notes recorded as part of the experiment.

In several instances, I used short code-words to denote a complex action. For example, I used the word *nogo* to denote checking the immediate surroundings for mooring balls, other vessels, shore features, man-made structures, debris, or any other kind of obstruction or hazard. In the current transcript, however, I replaced these code-words with longer and more descriptive wording.

The transcript is partitioned into a series of sections, depending on the strategy I employed or the outcome I desired.

Pre-launch Sequence

- ☐ Everything properly stowed away (cabin/cockpit/decks)
- ☐ Lift and drop the engine in the water
- ☐ Switch to Battery 1
- ☐ Pull up engine latch
- ☐ Attach throttle cable
- ☐ Prime the hose bulb
- ☐ Pull choke
- ☐ Start the engine by turning key
- ☐ Push choke
- ☐ Shut forward hatch
- ☐ Release jib sheets

- ☐ Remove mainsail cover
- ☐ Attach the main halyard
- ☐ Remove headsail cover
- ☐ Attach jib halyard
- ☐ Attach jib sheets
- ☐ Remove cover for the depth sounder
- ☐ Turn on depth sounder from instruments panel
- ☐ Cast off the mooring lines

Post-launch Sequence

- ☐ Connect rail
- ☐ Secure mooring lines
- ☐ Stow fenders in lazarette
- ☐ Choose a course (downwind)
- ☐ Locate mooring balls and boats ahead
- ☐ Steer through the mooring field
- ☐ Find a spot with no boats/moorings and leeway to head upwind for sails deployment

Hoist Mainsail

- ☐ Release mainsail straps
- ☐ Release the main sheet
- ☐ Release the vang
- ☐ Set heading upwind
- ☐ Secure tiller using a line
- ☐ Set engine throttle high enough to stay on course
- ☐ Grab winch handle
- ☐ Hoist the mainsail
- ☐ Cleat main halyard
- ☐ Centre the traveller
- ☐ Trim main sheet
- ☐ Trim vang

Plan Heading

- ☐ Scout horizon
- ☐ Locate nearby boats, mooring balls, and shore features
- ☐ Check wind direction

- ☐ Check sail trim
- ☐ Check waves for wind gusts
- ☐ Plan course with reference to landmarks
- ☐ Steer course (steer)
- ☐ Trim mainsheet

Hoist Headsail

- ☐ Hoist jib halyard
- ☐ Check on stuck sail
- ☐ Locate winch handle
- ☐ Tighten halyard using the winch
- ☐ Cleat halyard
- ☐ Secure winch handle

Lift Engine

- ☐ Turn off engine
- ☐ Release throttle cable
- ☐ Push down latch
- ☐ Lift engine up until it locks in the diagonal position

Sail

- ☐ Locate nearby boats, mooring balls, shore features and other hazards
- ☐ Check wind direction
- ☐ Check sail trim
- ☐ Trim headsail sheets
- ☐ Trim mainsheet
- ☐ Wind shift
- ☐ Trim headsail sheets
- ☐ Trim mainsheet
- ☐ Wind shift
- ☐ Trim mainsheet
- ☐ Check waves for wind gusts
- ☐ Check wind direction
- ☐ Locate nearby boats, mooring balls, shore features and other hazards
- ☐ Check sail trim
- ☐ Steer course
- ☐ Wind gust

- ☐ Trim mainsheet
- ☐ Trim headsail sheets
- ☐ Steer course
- ☐ Look at the chart
- ☐ Locate nearby boats, mooring balls, shore features and other hazards
- ☐ Check waves for wind gusts
- ☐ Check wind direction
- ☐ Check sail trim
- ☐ Steer course
- ☐ Trim mainsheet
- ☐ Trim headsail sheets
- ☐ Look at the chart
- ☐ Locate nearby boats, mooring balls, shore features and other hazards
- ☐ Check waves for wind gusts
- ☐ Check wind direction
- ☐ Check sail trim
- ☐ Trim mainsheet
- ☐ Trim headsail sheets
- ☐ Steer course
- ☐ Check wind direction
- ☐ Check waves for wind gusts
- ☐ Check sail trim
- ☐ Look at the chart
- ☐ Trim mainsheet
- ☐ Observe the heel of the boat
- ☐ Locate winch handle
- ☐ Secure winch handle
- ☐ Steer course
- ☐ Alter course to avoid crab traps
- ☐ Locate winch handle
- ☐ Trim headsail sheets
- ☐ Trim mainsheet
- ☐ Observe the heel of the boat
- ☐ Look at the chart
- ☐ Wind gust
- ☐ Check sail trim
- ☐ Trim mainsheet
- ☐ Trim headsail sheets
- ☐ Observe the heel of the boat
- ☐ Check sail trim
- ☐ Locate winch handle
- ☐ Observe the heel of the boat
- ☐ Trim mainsheet
- ☐ Look at the chart
- ☐ Wind shift
- ☐ Check tides

Daymarker Rounding

- ☐ Plan rounding the day marker (take wind gusts and shifts, shore, currents, and drift into account)
- ☐ Memorize the passage
- ☐ Automatic: Locate nearby boats, mooring balls, shore features and other hazards, wind, sail, water, steer, main
- ☐ Develop rounding strategy
- ☐ Tack
- ☐ Trim mainsheet
- ☐ Jib trim (find winch handle, move to lower side, trim jib, secure handle, move to the high side)
- ☐ Lower headsail to reduce speed for rounding
- ☐ Snagged a line with a foot
- ☐ Look at the chart
- ☐ Tack
- ☐ Wind dropped down
- ☐ Hoist jib
- ☐ Tack
- ☐ Observe near rocks
- ☐ Tack
- ☐ Check wind direction
- ☐ Trim mainsheet
- ☐ Trim headsail sheets
- ☐ Tack
- ☐ Monitor depth
- ☐ Heeling a lot
- ☐ Monitor day marker
- ☐ Depth
- ☐ Look at the chart
- ☐ Trim mainsheet
- ☐ Wind gust
- ☐ Monitor day marker
- ☐ Depth
- ☐ That's it
- ☐ Look at the chart
- ☐ Change course
- ☐ Jibe
- ☐ Trim mainsheet
- ☐ Trim headsail sheets
- ☐ Locate nearby boats, mooring balls, shore features and other hazards

- ☐ Check waves for wind gusts
- ☐ Horizon
- ☐ Paddleboarder
- ☐ Clouds, weather estimate

Sail Back

- ☐ Beam reach
- ☐ Automatic sailing most of the time
- ☐ Thinking about other things

Appendix B. Observations

In the course of my project, I collected countless observations in many forms. I used these observations to derive insights for the design process.

I've listed a few of these observations below in no particular order. I've identified the contributors by name – unless I was the contributor.

> "The wind particles shouldn't only be in front of you, but all around."
>
> *Senior sailor with moderate skills*

> "The model shouldn't be too idealized, i.e. too abstract"

> "Real time drift (current) is interesting [to experienced sailors], especially the behind the scenes computation. Maybe you can add more information about how it's performed."
>
> *Senior sailor with lots of off-shore experience*

> "Experienced sailors don't see the need for [the system], they are happy with the current tech"

> "Arrows [instead of particles] (abstract representations) are much more attractive to older sailors, who are used to similar graphical representations."
>
> *Senior sailor with lots of off-shore experience*

> "Pseudo-natural vs. abstract representations should not be the obvious design choice. Let's not put the cart before the horse; just because I thought particles looked cool, it doesn't necessarily mean they're also intuitive to everybody."

“Don’t you scientist-types use rubber ducks for research!? I heard in the news about a NASA project in the arctic with ducks.”

Sailing enthusiast

“Arrows should be able to change [in] length or width”

Senior sailor with moderate skills

“Was overwhelmed at first, said ’send it to me to use it,’ willing to give it a try”

Senior sailor with lots of off-shore experience

“Ways to visualize current: kelp, buoy, day marker, etc.”

“Camera is a massive bonus, you can see ahead of the boat even when down below”

Senior sailor with lots of off-shore experience

“Now, say you’re to somehow use the radar like they have ’em sonar contraptions, that’d be somethin’ actually useful, see?!”

Scruffy old sailor and shipwright

“Literally seeing the effects of the wind is easier to process than imagining the wind from a description via a typical wind instrument”

“Aggregating several forces (wind, current, speed) is hard to imagine, but easy to understand if visually available”

“Look into AIS integration, that’s a major helper in open ocean. Keeps ’em massive ships away.”

Off-shore sailor

“A combination of arrows and natural elements is preferable to some sailors”

> “There’s no stopping on a boat, dude; everything keeps moving all the time. You can’t like pull on the side of the road and stop all chill-like, like in a car. And then there’s mad gusts, and waves, and such. Jibing is hella-crazy, the boom goes, like whoosh, kah-pow! It’ll slash your melon right off!”
>
> *Teenager attending the sailing school*

> “Virtual objects should have a similar appearance and behaviour to real objects, but with a twist - a significant difference that makes it obvious that they are not real”

> “Information encoded in non-visual ways is significantly more cumbersome to understand.”

And last, when asked what he thinks about the system, this gentleman replied thusly: (we’re still not completely certain what it means)

> “[...]be sure to be shiverin’ yer timbers and bucklin’ yer swashes should you be rollin’ about the hoggin’ or careenin’ ashore, lest the brethren of the sea address yea that day, aaarrrggghhhh!
>
> Spread the word ’n don’t be forgettin’ to Stick to the Code!”
>
> *Rambunctious, wise-cracking, drunken sailor* on Sept 19, the International talk like a pirate day

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