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# Kilo Hōkū—Experiencing Hawaiian, Non-Instrument Open Ocean Navigation through Virtual Reality

## Abstract

In this article, we present our development of a virtual reality simulation of sailing on the Hōkūle‘a, a Polynesian double-hulled sailing canoe built in Hawai‘i in 1974, which completed its worldwide journey in 2017. The construction and sailing of this vessel is of significant importance to the Hawaiian cultural renaissance of the 1970s and 1980s; of particular relevance is Hawaiian wayfinding, the cultural practice of navigating across the open ocean to a destination without the use of maps or modern navigation instruments. By developing the simulation, we aimed to assist in the cultural preservation of the star navigation portion of Hawaiian wayfinding techniques, and to help to educate future generations of non-instrument navigators. The first implementation of Kilo Hōkū as a cultural heritage project in virtual reality was to test its viability as a tool for Modern Hawaiian wayfinders to use in classroom instruction, and its realism as an accurate reproduction of the Hōkūle‘a's sailing experience. The reaction to the simulation from current practicing Modern Hawaiian wayfinders was positive, and indicates that further study is warranted in testing the efficacy of the simulation for teaching Hawaiian wayfinding to future navigators, as well as preserving and spreading knowledge of Hōkūle‘a and of Modern Hawaiian wayfinding beyond Hawai‘i.

## 1 Introduction

The Polynesian Voyaging Society (PVS) was founded in 1973 in Honolulu, Hawai‘i with the purpose of developing and sailing a reconstructed Hawaiian double-hulled outrigger canoe on the open ocean, using non-instrument navigation techniques known as wayfinding. In this practice, the navigator uses numerous environmental data points, such as wind direction; cloud patterns; wave swell direction; star, moon, sun, and planetary position; and the sighting of ocean-faring birds to determine the vessel's position on, and to navigate across, the ocean with nearly the same accuracy as modern navigational instruments (Finney, Kilonsky, Somsen, & Stroup, 1986; Low, 2013, pp. 202–205; Howe, 2007, pp. 186–196). This practice is of cultural and historical significance to the Native Hawaiian population, whose ancestors practiced wayfinding for open ocean voyaging. It is a prime topic for preservation and further exploration in cultural heritage work and, as Ch'ng (2015) states, an

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opportunity to let the heritage community lead by defining genuine problems within their domains. With the intent of preservation and education, our team prototyped a simulation in a virtual reality environment on the HTC Vive in an attempt to aid in the learning about and teaching of Hawaiian wayfinding and the Hōkūleʻa's importance to Hawaiian culture. Users can experience being on board and sailing the vessel, view the stars and constellations, see the Hawaiian star compass in context, and apply Modern Hawaiian wayfinding techniques to navigate between two Hawaiian islands. We shared our simulation with six crewmembers from the Polynesian Voyaging Society and five astronomers from the ʻImiloa Astronomy Center. This article will give an overview of the sailing vessel Hōkūleʻa, the practice of Hawaiian wayfinding, and their joint importance to Hawaiian history and modern-day Native Hawaiian culture. It will then introduce our work to produce a simulation to assist in teaching the star navigation portion of Hawaiian wayfinding and the preservation of the experience of being on the Hōkūleʻa. We will also discuss reactions to the initial implementation, and potential for further development and experimentation as both an educational tool, and as a recreation and preservation of the sailing experience for the crew of the Hōkūleʻa as a cultural heritage project.

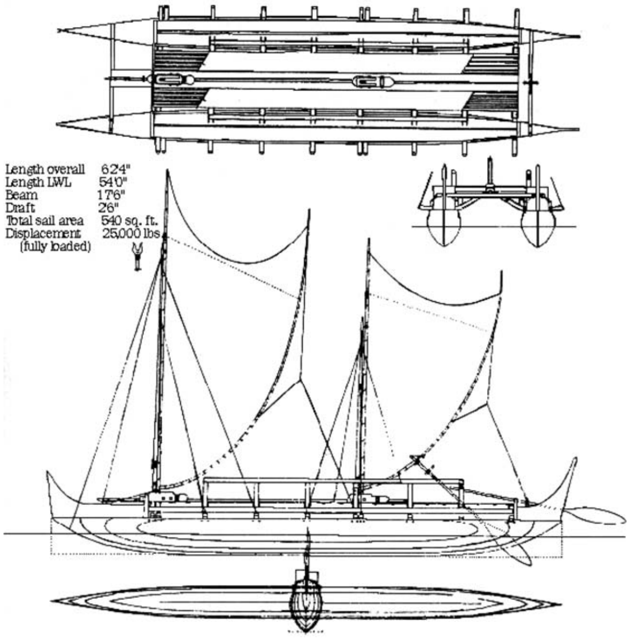

**Figure 1.** *Original construction drawings for the Hōkūleʻa. From "Founding the Polynesian Voyaging Society; Building Hōkūleʻa," by Ben Finney (http://archive.hokulea.com/ike/kalai_waa/finney_building_hokulea.html). © Polynesian Voyaging Society, reprinted with permission.*

## 2 History

### 2.1 Hōkūleʻa

Knowledge of traditional ocean voyaging canoe construction, sailing, and navigation practices were entirely lost to Native Hawaiian populations after colonization and the subsequent annexation of the Hawaiian Kingdom in 1898. Suppression of cultural practices by missionaries combined with western educational institutions and methods all but wiped out Native Hawaiian language and cultural practices (Low, 2013, pp. 22–23).

The modern renaissance of Hawaiian voyaging and non-instrument navigation began in 1973 with the founding of the Polynesian Voyaging Society by Ben Finney, Herb Kane, and Tommy Holmes. They sought to disprove the assertions made in the 1947 voyage of Thor Heyerdahl on the Kon-Tiki, and the subsequent writings of historian Andrew Sharp (Finney, 1979, p. 13). Heyerdahl and Sharp asserted that the Hawaiian Islands had been reached and settled by chance by early ocean voyagers, who simply drifted across the ocean with the prevailing currents and winds, who could not use complex sailing techniques, and for whom open ocean navigation could not have been possible in historic times. Their resulting conclusion was that Hawaiʻi (and much of Polynesia) was journeyed and settled by accident, not by intent (Heyerdahl, 2009; Sharp, 1956; Finney, 1979, pp. 10–11).

Finney, Kane, and Holmes set out to build and sail an historic reproduction of a Hawaiian double-hulled canoe from Hawaiʻi to Tahiti using only traditional non-instrument navigation techniques. Tahiti was chosen due to its historical connection to Hawaiʻi; anthropologist Taonui argues that the similarity in linguistics and oral history connects the migration of populations from Tahiti to Hawaiʻi and back (Howe, 2007, pp. 45–50). Plans for construction were drawn featuring a double-hulled

**Figure 2.** *Hōkūleʻa's arrival in Honolulu from Tahiti in 1976, by P. Uhl, 1976, https://commons.wikimedia.org/wiki/File:Hokule%27a.jpg. Used under Creative Commons Attribution-ShareAlike 3.0 Unported (CC BY-SA 3.0) license: https://creativecommons.org/licenses/by-sa/3.0/deed.en.*

**Figure 3.** *Hōkūleʻa's arrival in 2017 in Honolulu, Hawaiʻi after the 3-year Mālama Honua worldwide voyage. June 17, 2017.*

outrigger canoe (see Figure 1) based on PVS's research of other traditionally built Polynesian seafaring vessels and historic drawings recorded by earlier European explorers, as the original designs of Hawaiian canoes had been lost (Finney, 1979, pp. 22–23).

The decision was made to use modern-day materials for safety reasons, but to lash the hulls together using only ropes in the manner ancient Polynesians were depicted as doing. In addition, the hulls were kept closer together to avoid building a vessel that would be too modern; a similar reconstructed vessel built around that time but with hulls spaced further apart broke up under too much stress. Construction began in 1974, and was completed with help from both seasoned sailors and Native Hawaiian people from throughout Hawaiʻi (Howe, 2007, pp. 128–129; Finney, 1979, pp. 23–25).

The completed vessel launched in 1975 and was named Hōkūleʻa. This name translates to "Star of Joy," the Hawaiian name for the star Arcturus, which is the zenith star for the Hawaiian Islands (Low, 2013, pp. 44–60; Howe, 2007, pp. 128–129). Hōkūleʻa is a double-hulled sailing canoe 19 meters / 62 feet in Length Overall (LOA), with a beam (width) of 5.3 meters / 17 feet and a draft (distance between the waterline and the bottom of the hull) of 0.8 meters / 2.6 feet (see Figure 2). Her two masts were originally configured with a "crab claw" style sail, but can be retrofitted for an upside-down triangular type sail (see Figure 3). She can carry a crew of up to 16, and a total load of 25,000 lbs. At full sail speed with favorable winds, she can make 7–7.5 knots, and with boosts from wave swells accelerate up to 10–12 knots across the water (Howe, 2007, pp. 127–132).

Since her construction and launch, the Hōkūleʻa has sailed over 150,000 nautical miles throughout the Pacific, making landfall throughout Polynesia, Japan, New Zealand, and the west coast of the United States. Most recently she undertook a multi-year worldwide voyage from 2014 to 2017, the longest yet taken by any Polynesian voyaging canoe in modern history, in a cultural outreach effort titled "Mālama Honua" or "caring for our island Earth" (The Mālama Honua Voyage, n.d.). But before undertaking any of these endeavors, she had to prove the viability of the 1976 experiment by making the first trip to Tahiti.

The Polynesian Voyaging Society now had a traditionally styled vessel constructed in Hawaiʻi. But in order to sail to Tahiti using traditional methods, they had to search for a teacher outside of the islands, as the knowledge of non-instrument navigation had been mostly lost in Hawaiʻi. To teach these techniques and guide the initial voyage, they sought the guidance of Polynesian

Navigator Mau Piailug from the Micronesian island of Satawal in the Caroline Islands (Finney et al., 1986).

## 2.2 Modern Hawaiian Wayfinding

Non-instrument ocean navigation, hereafter referred to in general as "wayfinding," is the practice of sailing across open ocean without the aid of modern navigational instruments. Wayfinders are able to maintain a heading and map latitudinal position and distance traveled within their mind's eye by combining the observation of star location and movement; wave motion; wind cues; cloud conditions; bird and fish sightings; and sun, moon, and planetary position in the sky. Here we discuss the history and development of Modern Hawaiian wayfinding, and cover a small portion in detail relevant to Kilo Hōkū, specifically celestial navigation.

The work of the Polynesian Voyaging Society came to fruition in 1976 with the journey of the Hōkūle'a from Hawai'i to Tahiti, under the wayfinding guidance of Mau Piailug. It was the first time in modern history that an outrigger canoe was built in Hawai'i and successfully sailed from Hawai'i to a remote location, entirely using wayfinding techniques from his home of Satawal. This proved not only that it was possible, but that it was likely commonplace for Pacific Islanders to use wayfinding as a means of transiting the Pacific Ocean with intentional direction and destination in mind (Low, 2013; Howe, 2007, pp. 295–302).

The return trip from Tahiti to Hawai'i included in its crew a trained sailor named Nainoa Thompson. Thompson had been fascinated by Piailug, and learned as much of the art of wayfinding as he could from Piailug before the departure of the Hōkūle'a from Hawai'i to Tahiti. The return trip to Hawai'i from Tahiti on the initial voyage was conducted with modern instruments, and Piailug was not part of the crew; regardless, this gave Thompson an opportunity to observe and hone his sense and awareness of the stars, waves, and wind and how they interacted with, and could be used as, indicators of the heading for the sailing canoe. After his return to Hawai'i, Thompson spent time at the Bishop Museum planetarium, seeking to draw knowledge from the movement of the stars across the sky in a setting that allowed him to control the passage of time (Low, 2013, pp. 147–148). He later sought additional training directly from Piailug, and together they worked to hone Thompson's wayfinding abilities. In 1980, Thompson successfully replicated the original journey of the Hōkūle'a from Hawai'i to Tahiti, the first modern wayfinder to navigate the voyage.

Because the original practice of Hawaiian wayfinding as taught via oral tradition and practice has been mostly lost (Low, 2013, pp. 21–25; Kyselka, 1987, p. 37), the modern system was created by Nainoa Thompson based on the teachings of Piailug, combined with his own observations of the sky and stars and his experiences of sailing on a double-hulled sailing canoe, or wa'a kaulua, including the Hōkūle'a (Finney et al., 1986). What has been termed Modern Hawaiian wayfinding is the currently utilized method for traditional wayfinding navigators in the Hawaiian islands, and is the focus of our study on the cultural heritage of the practice.

Modern Hawaiian wayfinding is rooted in three navigational concepts at the core of open ocean navigation: knowing the direction you are sailing in, knowing the vessel's current location on the ocean and altering the course for corrections, and finally achieving arrival at the planned sailing destination (Finney et al., 1986, pp. 41–42). For direction and location, Thompson developed the Hawaiian star compass, a tool which is used to track the rising and setting location of stars on the horizon in relation to the sailing vessel. This compass divides the horizon evenly into 11.25° sections, with the major north, south, east, and west compass headings. This results in 32 compass points, divided into four quadrants, or north east, north west, south west, and south east. Thompson assigned the traditional Hawaiian names to the cardinal compass points and his own choice of Hawaiian words to the ordinal compass points, based on Hawaiian geography (see Table 1). Finally, a repeating series of names are used for each of the 11.25° compass points between the cardinal points, which repeat backwards from north to south, and likewise from east to west. Each of these compass points creates a "house" (see Table 2) that is 11.25° wide. Because house names repeat in each quadrant, the quadrant name is used in combination with the house, that is, manu malanai

**Table 1.** *Cardinal and Ordinal Compass Points Translated for the Hawaiian Star Compass*

| Compass Direction | Hawaiian Translation |
|---|---|
| north | ʻākau |
| north east | koʻolau |
| east | hikina |
| south east | malanai |
| south | hema |
| south west | kona |
| west | komohana |
| north west | hoʻolua |

**Table 2.** *Houses in the Hawaiian Star Compass*

| House | English Translation |
|---|---|
| haka | the emptiness |
| nā leo | the voices |
| nālani | the heavens |
| manu | bird |
| noio | noddy tern |
| ʻāina | land |
| lā | sun |

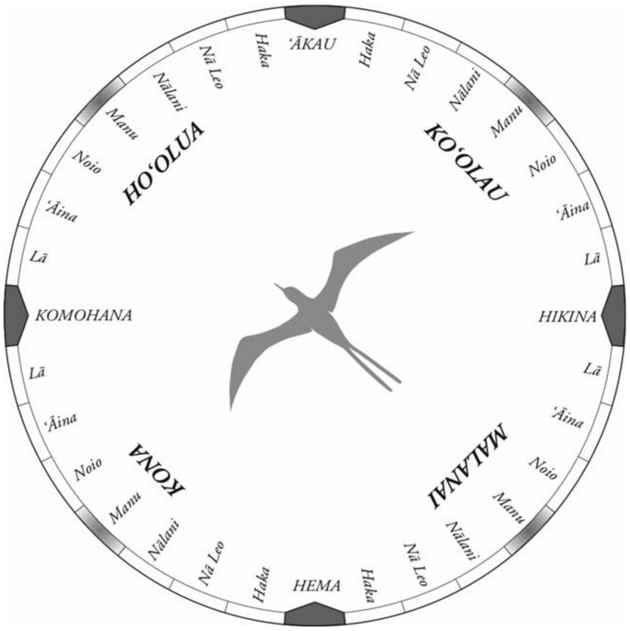

**Figure 4.** *The Hawaiian Star Compass. From "Star Compasse." The Hawaiian Star Compass was developed by Master Navigator Nainoa Thompson (http://archive.hokulea.com/ike/hookele/star_compasses.html). © Polynesian Voyaging Society, reprinted with permission.*

would be directly southeast; the exception is the cardinal compass points which are their own house. Combined, they create the Hawaiian star compass, as developed by Thompson (see Figure 4). North on the star compass always points to true north, which results in the northern point of the star compass being directly in line with the north star, Polaris, and the southern point of the star compass being in line with the upright Southern Cross (Howe, 2007, pp. 188–189; Finney et al., 1986, pp. 53–55; Kyselka, 1987, pp. 95–98).

To navigate using this star compass, the waʻa is pictured in the middle with the star compass oriented north–south. Aboard the Hōkūleʻa there are physical markings on the vessel's railings for the star compass points; this aids the navigator in accurately measuring the width of each house. The waʻa is oriented to point at any one of the assigned compass points, or houses, at the horizon; this is the given course of sailing direction for the vessel. The rising and setting of the stars during the night guide the navigator, as specific stars will rise and set in specific locations on the horizon. This location, measured as a clockwise angle from true north along the horizon, is a star's azimuth. The azimuth will change depending on the location of the waʻa on the ocean, and indicate correct compass points or headings for navigation. This requires memorization of hundreds of stars, their rising and setting houses, and the change of azimuth and rising time depending on latitude and longitude of the waʻa (Howe, 2007, pp. 190–194; Finney et al., 1986, pp. 42–43). Bearing this knowledge, the navigator can orient against specific stars as they move through the sky, sailing toward a specific house and maintaining that course relative to rising and setting stars. Thus, the navigator is able to reliably estimate the direction that the vessel is sailing in.

Latitude, the north–south measurement of distance from the earth's equator, is determined in wayfinding by measuring the altitude, or angular height, of a given star above the horizon. Polaris, the north star, maintains a

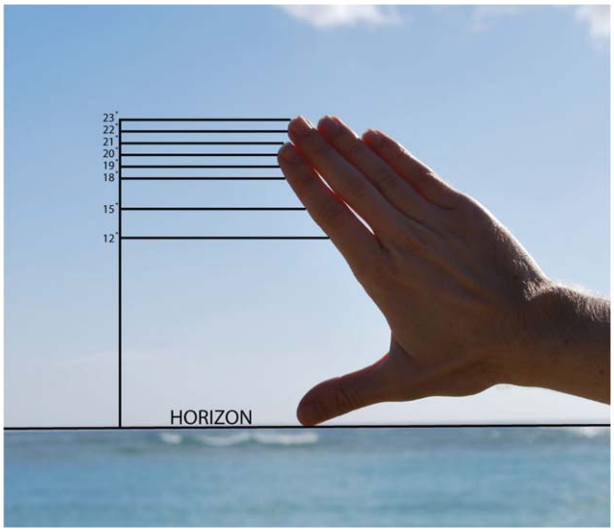

**Figure 5.** *Aligning the hand with the thumb against the horizon to judge the angular height of celestial objects.*

specific fixed altitude in the sky at the latitude of Hawai‘i, 21° north. Because Polaris is effectively stationary in the night sky, it can be used as a reliable fixed object for measuring altitude at different latitudes. In order to map this height, Thompson developed a method for measuring using his hand held up and aligned with the horizon. By holding the hand in an L shape with the thumb at a right angle to the index finger, and placing the thumb against the horizon, a wayfinders can measure the height of celestial objects from the horizon to physical features on their hand (see Figure 5). For example, if Polaris is at the height of the end of the middle finger, then Thompson knows he is at 21° north latitude. Thompson mapped out additional heights against his hand, determining the correct measurement for various latitudes against Polaris. This method can be extrapolated to measure the height of any star against the horizon, once calibrated against Polaris for that person’s specific hand size (Howe, 2007, pp. 190–194; Finney et al., 1986, pp. 56–57).

However, Polaris or other stars are not an always available indicator. Polaris is not visible below the equator, and cloud cover or other environmental factors may make sighting specific individual stars impossible. To counter this, Thompson made further observations regarding pairs of stars. First, at different latitudes different pairs of stars rise and set in relation to each other. Star A sets before star B at one latitude; at another star B will set before star A. At a specific latitude, they will set simultaneously, which is a reliable indicator of the latitude of the vessel (Howe, 2007, pp. 192–194; Finney et al., 1986, p. 58).

Furthermore, the vertical alignment of pair stars and their altitude from each other and the horizon can also be used to determine latitude. Certain pair stars will align vertically when transiting the celestial meridian, a line drawn bisecting the sky starting on the horizon at true north, through the zenith directly overhead, and then back down to the horizon at true south, perpendicular to the horizon. Thus, two vertically aligned stars in the night sky are indicative of being oriented against the observer’s celestial meridian, and the lower altitude star of the pair can then be used to indicate distance to the horizon, and subsequently the latitude of the navigator. This further expands the navigator’s toolset for determining latitude out at sea beyond sighting single stars, but requires memorization and recall of the rising and setting pairs, and pairs that align at the celestial meridian (Howe, 2007, pp. 192–193; Finney et al., 1986, pp. 56–67).

By using celestial navigation and positioning, the wayfinder is able to determine heading and latitude. The last piece of determining the current location is obtained by measuring how on or off course the navigator maintains the sailing heading over a period of time with relation to wave movement and where the wind allows the navigator to actually sail. Thompson developed a chart for indicating distance traveled over a day, which combined with periodic estimates of the vessel’s speed, allow a determination of whether the navigator has maintained course, and how off-course the person currently is based on the same house widths of 11.25° used for the star compass (see Figure 6). This is known as dead reckoning, and is the means via which the navigator is able to determine location based on travel time and distance from the original set off point (Howe, 2007, pp. 194–196; Finney et al., 1986, p. 56).

The final piece of wayfinding is achieving landfall at the intended destination. Instead of trying to find a small island, wayfinders instead search for a wider range, or

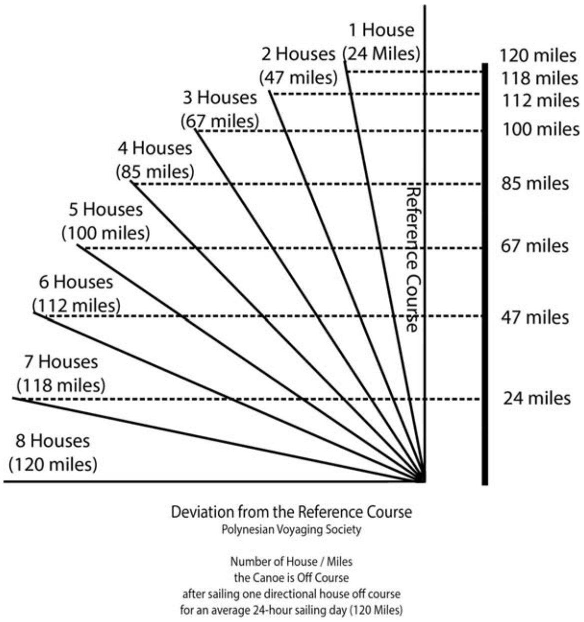

**Figure 6.** *Deviation chart from the reference course. Based on “Estimating Position,” by the Polynesian Voyaging Society (http://archive.hokulea.com/ike/hookele/estimating_position.html). © Polynesian Voyaging Society, reprinted with permission.*

“screen” of islands which can be used to then reorient and navigate toward the specific destination. By using this method of “expanding the target,” the wayfinder instead aims for a general area of the ocean, then becomes more specific as the destination approaches.

To spot the presence of an island, which may not be visible in the distance at the horizon, the navigator will look for a number of environmental clues. Seafaring birds that leave land to fish during the day and return to land at night are an excellent indicator of the presence of nearby islands. The navigator will notice a change in the way the wave swells feel under the vessel, as refraction of waves around an island will carry out to ocean and change the directional swell patterns. Finally, cloud patterns are different near an island as opposed to open ocean, and are often indicative of a landmass beneath, even when the landmass cannot be seen at a distance (Finney et al., 1986, pp. 46–47, 58).

By combining the tools of the environment, wayfinders are able to navigate across open ocean to a chosen destination with surprising accuracy. This resurgence of the practice in Modern Hawaiian wayfinding has spread to other Pacific Island nations that have lost their own wayfinding methods, and has resulted in their own adaptations based off Thompson’s developed system of wayfinding.

## 3 Purpose of the Kilo Hōkū Virtual Reality Simulation

Since Thompson’s initial instruction in, and reconstruction of, Modern Hawaiian wayfinding, more formal methods have developed for passing on the practice. Wayfinding methods are currently taught in Hawai‘i via an instructional classroom setting, combined with direct stargazing or within a planetarium, typically at the Bishop Museum in Honolulu. Those who continue to study advanced methods are usually chosen as a crew member of one of the ocean-faring wa‘a kaulua, one of which is the Hōkūle‘a. However, due to the scarcity of opportunities to be on board a Hawaiian seafaring vessel, it is difficult for the majority of students to gain practical experience in a real night-time open ocean setting on an actual wa‘a kaulua. There is only one Hōkūle‘a, and it is not commonly available as a training vessel to students of wayfinding. Furthermore, other Polynesian open ocean sailing vessels throughout Hawai‘i and elsewhere in the Pacific are not routinely available for training, or do not make the kind of deep ocean voyages that would be conducive to learning Modern Hawaiian wayfinding in practice. This lack of opportunities for training in real-world situations is a prime opportunity for developing a technical solution, grounded in cultural heritage as per Pujol and Champion (2012).

Kilo Hōkū, which translates as “to observe and study the stars,” was developed to fill this opportunity gap, to help enhance the learning and teaching of Modern Hawaiian wayfinding techniques, and to help preserve and spread awareness of the cultural heritage of the Hōkūle‘a. It is an additional method of preserving wayfinding knowledge and passing it on to future generations. The simulation is also a tool for those learning wayfinding. It assists in the initial teaching of methods and tests existing knowledge within a virtual environment. By placing the user in virtual reality on a wa‘a kaulua in the ocean, it gives the user an opportunity to learn and experience first-hand what could only otherwise be experienced on an ocean-faring vessel, much less on the Hōkūleʻa herself. To our knowledge, Kilo Hōkū is the first virtual reality simulation of a Polynesian voyaging waʻa kaulua ever developed, and the first to apply the celestial navigation portion of Modern Hawaiian wayfinding techniques in context in a virtual environment.

Because Native Hawaiian wayfinding is so tightly tied to the person, the waʻa, and the environment, virtual reality is well suited to simulating this task. There are no tools or physical objects beyond the waʻa that are used in wayfinding—the navigator must use the surrounding world to observe and examine clues for orienting in space. These environmental clues can potentially all be reproduced in a virtual environment.

Away from visible land, wayfinders estimate speed in nautical miles per hour, or knots, via visual timing of sea foam or object movement past the waʻa. We could, for example, calculate movement speed in the simulation, then generate movement of a texture directly adjacent to the waʻa on the surface of the water representing bubbles to simulate this calculation by the wayfinder. An artificial marker in the simulation moving past the waʻa may also be used to aid in learning this technique.

Wayfinders also navigate by signs other than stars; one method is by feeling the direction of long-form wave swells, which tend to be predictable at sea over long periods of time (Howe, 2007, p. 190). By changing the direction, amplitude, and frequency of long-form swells in the simulation and their effect on movement of the waʻa, we could simulate how wayfinders identify direction, and the way it affects the feeling of movement for the user. The simulation can be altered to generate and give direction to wave swells, which are currently randomly generated.

When attempting to make landfall, wayfinders pay particular attention to any animals in the habitat, specifically seafaring birds that can be followed as they return to land. We could add the presence of sea birds flying about as the user approaches a landmass, but before the landmass is visible. Greater detail could be added by generating a random number of birds, having them fly out from land, then return to land at random intervals.

In the sky, cloud patterns also change depending on the presence of a landmass; clouds will change shape, bunch up, or have a sudden gap where there are higher elevations beyond the horizon. Presenting this phenomenon in the simulation could be done with texture effects on the horizon as an island approaches, or by changing the background cloud patterns in the distance.

In addition to positioning the stars at night, the wayfinder tracks the position of the sun during the day. By adding a virtual hand to the simulation that could be swapped out for the controller model on a button press, we could allow the user to mark the position of the sun in the sky to measure the time of day. This virtual hand could also be used for measuring star altitude at night.

To keep track of relevant rising and setting star pairs and their location relative to the waʻa, there are markings along each of the railings. These are set at the requisite 11.25° intervals as mapped out from each of the navigator's seats aft of the waʻa. Using these markings, the wayfinder accurately aligns the waʻa against the star compass houses. He or she then maintains this alignment while sailing, and will tie rope on the railing or use another indicator to keep track of the particular marking used. Within the simulation we could display these markings on the waʻa, then allow the user to highlight or track any number of them via either a pointer or up-close physical interaction.

Finally, wayfinders also track celestial bodies other than the sun and stars. We could pull additional data on planetary and moon positions, and add them to the simulation to provide additional tracking points for users to practice against. This could be taken to a much more complex level than we currently allow by letting the users enter in date, time, longitude, and latitude to display exact night sky conditions at their current location.

As demonstrated, there are several portions of wayfinding that are well suited for re-creation within a virtual environment. Our focus for the initial prototype has been the celestial navigation and star compass portion of wayfinding, and the presentation of a waʻa in a virtual environment.

In the development of this project, we have consulted extensively with subject matter experts to ensure accurate reproduction of wayfinding methods. This project

**Table 3.** *Sailing Simulation Comparison*

| Title | Incorporates Polynesian Vessels | Virtual Reality Capable | Has Navigation | Has Celestial Navigation |
|---|---|---|---|---|
| VR Regatta[1] | No | Yes | Basic Compass | No |
| VRSailing[2] | No | Yes | No | No |
| Sailaway[3] | No | No | Full Map | No |
| Sail Simulator 5[4] | No | No | Full Map | No |
| **Kilo Hōkū** | Yes | Yes | No | Yes |

[1] https://www.marineverse.com/
[2] http://www.betomorrow.com/vrsailing-is-now-available-on-steam/
[3] https://www.sailawaysimulator.com/
[4] http://www.sailsimulator.com/

also provides a unique opportunity in cultural heritage preservation work; the subject of the project is a sailing vessel that currently exists, and is also of historic and cultural importance to the Hawaiian people. Because of this, we are able to get direct access to the source of the material—both the vessel used for sailing in order to assure that our simulation provides an accurate reproduction, and to the subject matter experts and practitioners of Modern Hawaiian wayfinding, to ensure that our information about and representation of wayfinding are also accurate.

## 4 Related Prior Work

We build on others' published material, commercial software, and educational work done to accurately recreate conditions for other historic seafaring vessels, and to display this work in a simulated virtual environment. Barreau et al. (2015) found that by creating a to-scale simulation, they were able to give anthropological insight to the sailing of an 18th-century French vessel. It also gave insight to how the vessel may have potentially handled on the open ocean, what types of conditions the crew might have lived in due to the amount of space provided, and the number of sailors on board listed in the crew manifest.

Castro and Fonseca's (2006) work to reproduce the sailing conditions on board a 17th-century Portuguese vessel gave guidance on what information to gather about the vessel to reproduce it in virtual reality. Their efforts parallel those of the original builders of the Hōkūle‘a, who did not have existing vessels to draw upon in their reconstruction of a double-hulled sailing vessel. We also took guidance on their work to reconstruct a virtual model in order to grant others access to a simulation of the physical reproduction being constructed. This again looks toward accessibility and availability issues with items of cultural heritage.

We reviewed existing commercially available sailing simulations which aim to realistically simulate the sailing experience (see Table 3). Two are available in virtual reality. Though they do simulate sailing on vessels such as yachts and traditional instrument-based navigation, none include sailing on a Polynesian sailing vessel of any type, nor do they include navigation using Modern Hawaiian wayfinding methods.

We also reviewed existing commercially available stargazing software (see Table 4). Of these, three were VR capable. Stellarium does have a Hawaiian star compass package available for download, and has a VR community project available. However, none of the stargazing software reviewed places the user in context on a wa‘a kaulua in the middle of the ocean, and do not incorporate sailing navigation into the software. Two of the simulations are also clearly tech demos, and do not allow alteration of the time or location in viewing of celestial objects, presenting only a stationary predetermined viewpoint for observation.

**Table 4.** *Stargazing Software Comparison*

| Title | Virtual Reality Capable | Includes Hawaiian Star Compass | Dynamic Location Placement |
|---|---|---|---|
| Stars[1] | Yes | No | No |
| Star Chart[2] | Yes | No | No |
| Starsight VR[3] | Yes | No* | Yes |
| Stellarium[4] | No | Yes | Yes |
| Bishop Museum Planetarium | No | Yes | Yes |
| **Kilo Hōkū** | Yes | Yes | Planned |

[1] http://store.steampowered.com/app/501440/Stars/
[2] http://www.escapistgames.com/sc.html
[3] http://starsightvr.org.uk/
[4] http://www.stellarium.org/
* Adaptation of Stellarium in VR; could possibly import star compass

Our review of the selected existing software solutions finds that they do not incorporate all elements of or cultural context for teaching about the Hōkūleʻa and Modern Hawaiian wayfinding. Bishop Museum's planetarium, used for research and creation of the wayfinding system utilized today (Low, 2013, pp. 147–148), does incorporate a large portion of the data about celestial navigation, but lacks the context of being placed on the vessel in the ocean.

Each of these programs, while independently useful, have not previously been combined to teach wayfinding in context on a waʻa kaulua in virtual reality.

## 5 Method

Inspiration from the prior work of Barreau et al. (2015) guided our efforts to generate a smaller scale simulation with a focus on the ocean, the waʻa kaulua, and the celestial sphere around the user. Efforts were made to retain realism in the simulation of the ocean, the scale and recreation of the waʻa kaulua, and the accuracy of the location of stars in the sky. Ribbens and Malliet (2010) have shown that by focusing on realism in the simulation, we improve the users' sense of presence and their focus on the experience of the simulation, instead of awareness that they are in a simulation. Due to restrictions on time, the space that the simulation occurs in is of a smaller scale than reviewed previous work, on the matter of 2–3 square miles versus multiple miles of open ocean.

In developing the Kilo Hōkū simulation, care was taken to consult with subject matter experts in wayfinding: Kaʻiulani Murphy, a navigator on portions of the 2000, 2004, 2007, and 2017 voyages of the Hōkūleʻa and a teacher of wayfinding at Honolulu Community College and the University of Hawaiʻi at Mānoa, and Chad Kālepa Baybayan, one of the original crew members of the Hōkūleʻa's maiden and numerous subsequent voyages, and a master wayfinder. Other feedback was gathered from current and past crew members from the Polynesian Voyaging Society, and astronomers from the ʻImiloa Astronomy Center at Hilo closer to completion of the project.

The HTC Vive was chosen as the virtual reality headset for this project due to the low cost of implementation and the reasonable fidelity of tracking for both the headset and the controller wands, which allow for easier simulation use by those who may not have familiarity with interacting in virtual reality environments. In particular, the concern was to make the platform as approachable as possible, so that the user can concentrate on the experience inside of the simulation.

The simulation was developed using the Unity 3D game development engine, which allowed for easy creation of environments and programming due to the modular nature of the system and available packages it provides, and the foundational support for the HTC Vive virtual reality headset. The Ocean Community Next Gen[1] package allowed for accurate recreation of ocean conditions and buoyancy effects in an effort to immerse the user further in the simulation. The VRTK[2] library was utilized to provide menu and environment interaction within the simulation. Finally, the SteamVR library allowed for display of the simulation in the HTC Vive and handled the majority of the stereoscopic display rendering of the simulation, as well as positional tracking and interaction with the VR Headset and the control wands. Effort was made to keep the simulation as realistic-looking as possible.

An audio element in Unity 3D was placed adjacent to the user's camera in the environment, tracking with head movement, and allowing for positional audio effects. It has been shown that by adding spatial sounds to the environment, presence is enhanced within a simulation (Kobayashi, Ueno, & Ise, 2015). This was used to play the sounds of ocean waves and wind, but no other audio elements were added (e.g., footsteps when the user moves about the canoe). No background music is present in the simulation in order to provide as much immersion as possible. By creating a natural, 3D soundscape that the user would expect in this situation, immersion is enhanced (Hoskinson & Pai, 2007; Lumbreras & Ramírez, 2010).

The celestial sphere, which contains the stars via which the user navigates, was constructed from high-resolution images obtained from NASA's Scientific Visualization Studio.[3] The default celestial sphere texture was constructed from the "celestial coordinates image" from NASA, upon which constellations were placed using the "constellation figures in celestial coordinates image" from NASA. Finally, star lines, which are visual indicators of stars specifically used in wayfinding, were generated using information from Starlab (2008). The images were combined using Photoshop to enhance prominent stars in constellations, and then scaled down in fidelity in order to fit inside of the texture memory boundaries imposed by the Unity 3D engine. The resulting images were imported into Maya to generate the celestial sphere by flipping the texture normals to make them render on the interior surface of the sphere. Each major constellation was constructed with an object in Unity 3D with a collider, which when interacted with displays the sky texture with the specific constellation displayed (see Figure 7). The user is placed in the center of this celestial sphere, giving the appearance of the night sky.

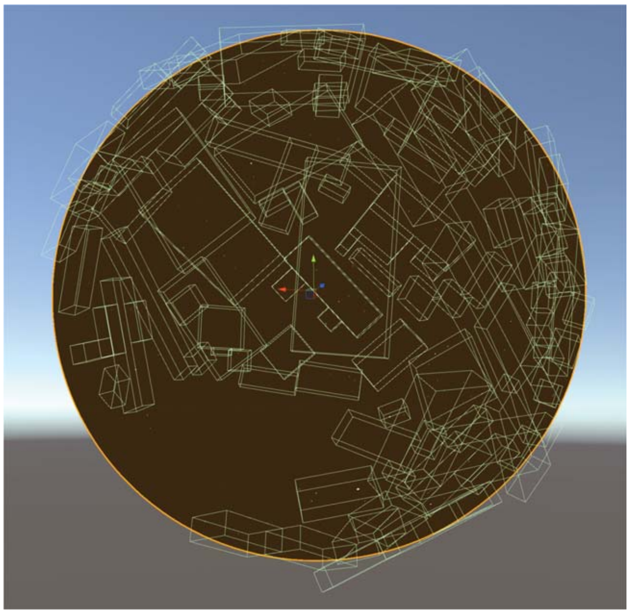

**Figure 7.** *Exterior view of the celestial sphere with colliders.*

The 3D model replica of the Hōkūleʻa (see Figure 8) was developed by 3D artist Mike Pai; creation of the model was funded by Bishop Museum's US Department of Education Native Hawaiian Education program grant S362A110069, "All Together Now: A Model Partnership for Improving Native Hawaiian Middle School Education," in partnership with Polynesian Voyaging Society and the University of Hawaiʻi College of Education. Permission was granted for use of the model in our simulation for educational purposes. Our own textures were added to bring the look and feel of the model as close as possible to the modern appearance of the Hōkūleʻa, and the model was scaled to 62 feet long to match the dimensions of the Hōkūleʻa (Howe, 2007, p. 129; Low, 2013, pp. 32–33).

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1. https://github.com/eliasts/Ocean_Community_Next_Gen
2. https://github.com/thestonefox/VRTK
3. https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3895

**Figure 8.** *Side view of the Hōkūleʻa 3D model in perspective.*

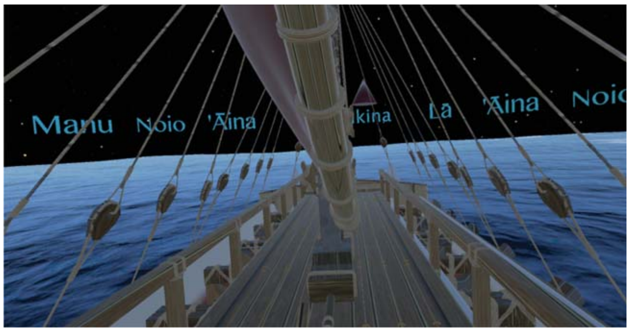
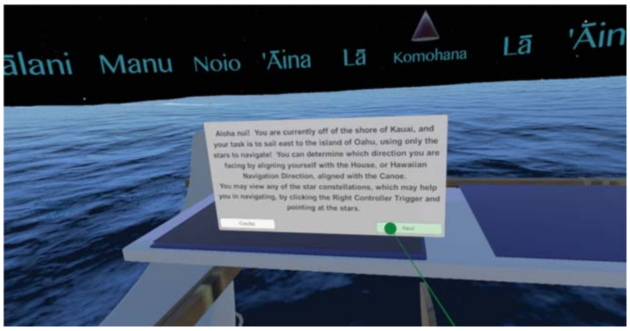


**Figure 9.** *User's view on the Hōkūleʻa model at the start of the simulation.*

## 6 Implementation

Upon donning the VR headset, the user is placed directly on the aft (rear) deck of the canoe, which is floating on the open ocean adjacent to a simulated island (see Figure 9). The night sky, oriented for July at the latitude of the Hawaiian Islands at 21° north, is displayed in a sphere around the user, with the lower half obscured by the ocean horizon, giving the appearance of the actual celestial sphere around the planet Earth.

An instructional menu mounted to the canoe directly behind the user when they start the simulation guides them through each of the available controls, and offers a brief history and tutorial to instruct them on how to proceed in the simulation (see Figures 10 and 11). Each page of the menu is navigated by touching the right controller touchpad to bring up an interaction pointer, and activated by clicking the same touchpad while the pointer is directed at the Next button on the menu display.



Aloha nui! You are currently off of the shore of Kauai, and your task is to sail east to the island of Oahu, using only the stars to navigate! You can determine which direction you are facing by aligning yourself with the House, or Hawaiian Navigation Direction, aligned with the Canoe.
You may view any of the star constellations, which may help you in navigating, by clicking the Right Controller Trigger and pointing at the stars.

**Figure 10.** *The instructional menu with the pointer, the Hawaiian star compass in the background.*

**Figure 11.** *User interacting with the menu under instructor guidance.*

After reading through each of the instructional menu pages, a controls guide is displayed, and can be removed from display or recalled with a menu button press on the left controller (see Figures 12 and 13). A credits menu is also available after reading through the instructions.

The canoe deck may be freely walked upon within the confines of the boundaries created by the Steam VR "safety fence," with minimum bounds of 2 × 1.5 m (see Figure 14). Steering and sailing the canoe may be achieved by using the grip buttons on either controller to take hold of the steering paddle (see Figures 15 and

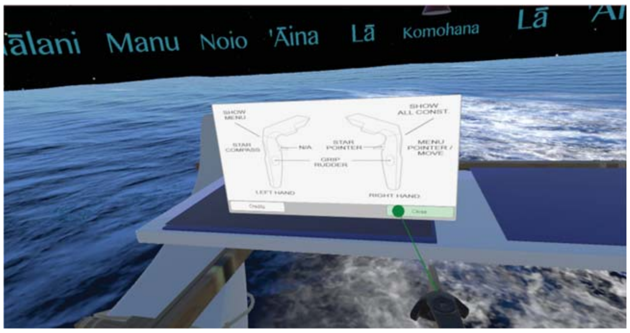


**Figure 12.** *Instructional menu with the controls shown, the Hawaiian star compass in the background.*

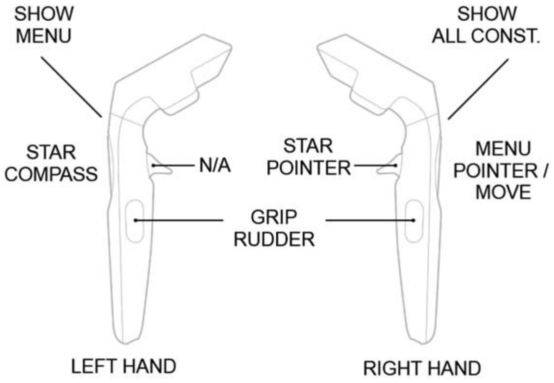


**Figure 13.** *Controls for the HTC Vive in the Kilo Hōkū Simulation.*

**Figure 14.** *View of the user's placement on the Hōkūle'a model in the simulation.*

16). Doing so causes the canoe to be propelled forward, and direction may be changed by moving the paddle left or right, which causes the canoe to steer in the opposite direction.

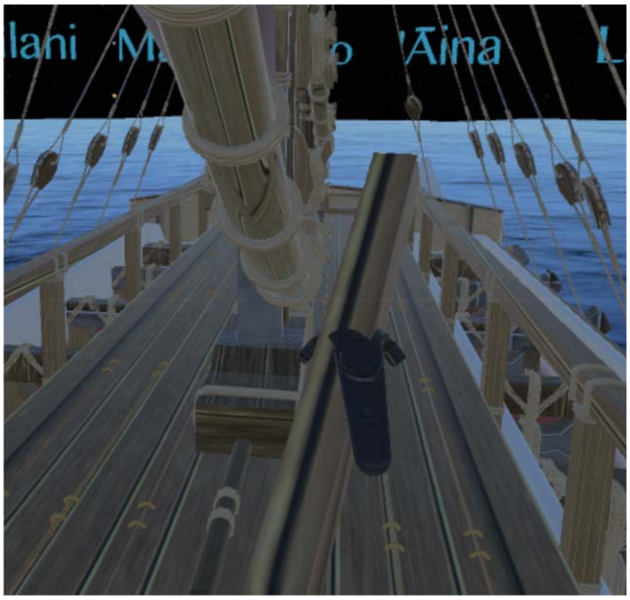


**Figure 15.** *Steering the canoe with an HTC Vive controller on the paddle.*

**Figure 16.** *User steering the canoe with the HTC Vive controller under instructor guidance.*

While moving, the canoe is affected by the wave pattern of the ocean simulation, which can cause it to pitch or roll depending on wave intensity. Care was taken to balance the amount of wave motion to reduce the incidence of motion sickness within the simulation, while still maintaining a realistic feel. The simulation is run with a gentle rolling ocean wave setting that conveys motion without being overly rocky or harsh.

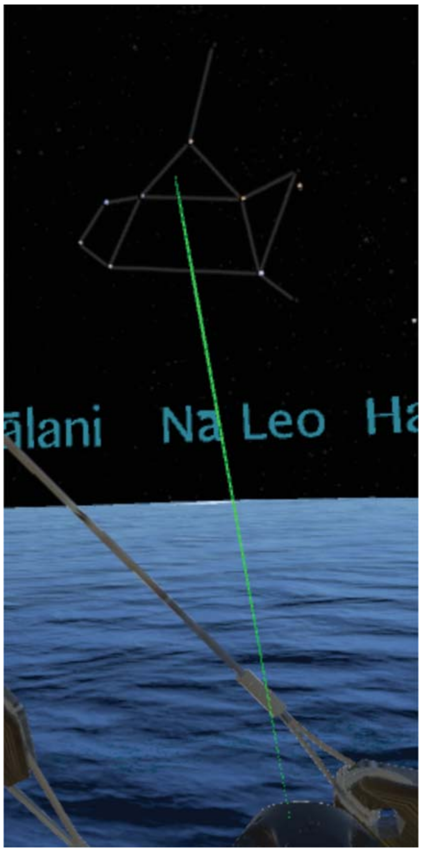


**Figure 17.** *Highlighting a constellation in the simulation using the pointer.*

Clicking and holding the right controller trigger button generates a ray emanating from the controller. This ray line allows the user to highlight constellations in the simulated celestial sphere by directing the ray to intersect a set collider for each constellation. All known western constellations are included in the celestial sphere, though only those which show above the horizon in the simulation may be interacted with via pointing (see Figures 17 and 18). The user may easily learn about or reinforce existing knowledge of the night sky using this method to show and confirm constellations in relation to the Hawaiian star compass (see Figure 19). All constellations may be made visible at once by clicking the right controller menu button, allowing them to be toggled on or off.

**Figure 18.** *User highlighting a constellation in the northeastern (Ko'olau) sky under instructor guidance.*

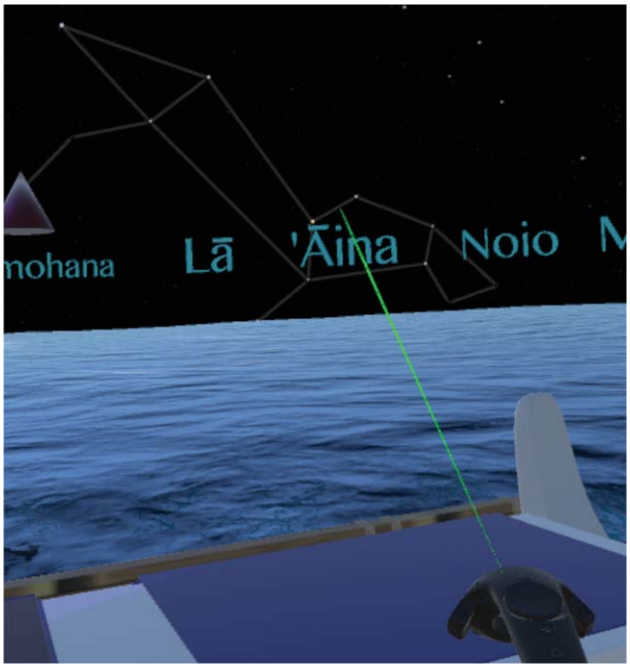


**Figure 19.** *Highlighting a constellation in the simulation against the Hawaiian star compass.*

A star compass, the tool used in wayfinding for indicating where stars rise and set on the horizon, is placed in a 360-degree circle around the user. This is used to indicate sight lines on stars close to the horizon, replicating the same method used in wayfinding. The names of the directions and offsets in the star compass are in Hawaiian (see Figure 20). It may be toggled on or off by clicking the left controller trackpad button.

The goal of the simulation is for the user to sail from the island of Kauaʻi to the island of Oʻahu using the

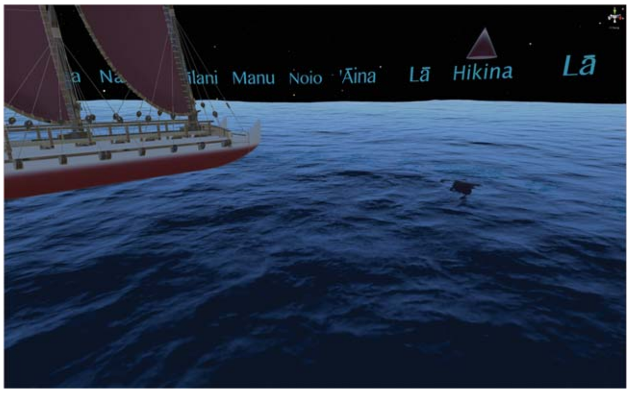


**Figure 20.** *The Hōkūleʻa model in the ocean simulation with the Hawaiian star compass.*

orientation of the stars on the horizon and in the sky to maintain a heading. Once the user has sailed within a preset distance of the island of Oʻahu, a menu appears with a message notifying them of completion of the simulation, with an option to reset to the beginning.

The simulation was kept simple and straightforward in order to aid completion in about 5 minutes. This allows multiple users to experience the simulation in a classroom or public conference setting.

For public conference demonstrations and exhibitions, cultural heritage experiences in a VR headset are typically limited to a single user at a time interacting with the simulation, and are not inclusive of others wishing to view or understand the content. Alternatively, if there is a secondary screen, it is typically a flat view, and is tied closely to the viewpoint of the user, potentially resulting in eye strain and nausea. Instead, we addressed this with a stereoscopic 3D live view of the user's experience simultaneously presented on a 55-inch 3D TV adjacent to the simulation area. To reduce eye-strain and potential nausea, the audience's view was created by first smoothing the VR user's head position and orientation (Guagliardo & Leigh, 2017). Observers were able to don stereoscopic glasses and share the viewpoint of the user in the simulation, thus expanding the experience beyond just the user wearing the VR headset. In this manner, audience members could see in 3D what the VR user was experiencing while waiting for their turn. This consideration is often glossed over when creating cultural heritage experiences, and warrants further adoption, particularly in convention and museum settings.

## 7 Results

The simulation prototype was tested by six crewmembers, two of whom are wayfinding instructors from the Polynesian Voyaging Society, and five members of the ʻImiloa Astronomy Center at the University of Hawaiʻi at Hilo. As subject matter experts, all had positive reactions, indicating interest in the simulation being further developed and utilized to help extend the reach of wayfinding education, as well as granting further exposure to the Polynesian Voyaging Society's educational mission. One reaction was that the tool could be used to speed learning of the concepts presented in wayfinding by providing more opportunities for simulating the experience.

Students of wayfinding who were shown the prototype stated that the simulation could potentially give them additional experience they would be unable to earn without being on a waʻa kaulua on the open ocean. One stated that it placed the star compass "in context," which was difficult to do while learning from the paper materials provided in class. Additional suggestions were provided on ways that the simulation could be further developed for teaching specific techniques of wayfinding, including the ability to "sight" stars at different heights from the horizon.

One PVS navigator remarked at how realistic the simulation "felt" as the vertical bobbing of the vessel with the ocean currents made her seasick. In virtual reality, where the emphasis has always been to minimize motion sickness, this was one of the rare occasions where it appeared to enhance the realism of the experience. Another navigator noted that the simulation would be well suited for areas with light pollution, as students are not able to view the night sky in or adjacent to major cities, granting accessibility to these populations. The same navigator noted that there was a small mistake in our simulation regarding the accuracy of the star compass lining up with the North Star—an item we have since resolved, but which shows that the simulation is close to realistic in its representation of Modern Hawaiian wayfinding.

## 8 Discussion and Future Work

While the initial version of the program only implemented basic sailing controls and constellation identification, it was well received by members of the community that teach and study wayfinding. Furthermore, it lays the foundation for adding all the other aspects of non-instrument wayfinding, and additional knowledge testing tools for educators.

Future enhancements to the simulation to address the remaining wayfinding elements are under development. With regards to celestial navigation, users will have the ability to identify and mark particular named stars in the celestial sphere. The celestial sphere will be rotatable around the Earth's simulated center axis to denote the passage of time, and allow the user to identify rising and setting stars by their intersection with the star compass at the horizon. Users will be able to set the latitude they are present at, identify particular changes in star position due to differing latitudes, and adjust latitudinal position to view these changes in real time. Additionally, the user will be able to add markers on the railing of the wa‘a to simulate location of the rising and setting of key stars in relation to the orientation of the wa‘a.

Wayfinding elements to be added include simulation of the vessel's speed via bubble movement; the direction and pitch of the wa‘a as waves move through the vessel; the presence of seabirds in relation to land; the addition of cloud formations in relation to land; the position of the sun during daylight hours; additional nighttime celestial bodies such as the moon and planets; and finally, the ability to display a virtual hand to allow the user to measure star height from the horizon as wayfinders do.

For testing knowledge on wayfinding, we are working with our subject matter experts to develop a teacher interface which can be used to add or remove information from the simulation. This can be used to do a knowledge check, for example, by removing parts of the star compass and asking the user to identify direction based on stars present at their current latitude. The teacher can then assess competency and either train or reinforce knowledge within the simulation. This will be performed via the external 3D view on a secondary monitor, and via keyboard commands input to the simulation.

We have also discussed adding virtual agents, as described by Champion (2015), to enhance both the immersiveness of the simulation, as well as the cultural heritage representation; for example, by having the virtual agent speak in Hawaiian with subtitles, and by incorporating pule (prayer or ceremony) and protocols used by the Hōkūle‘a crew before, during, and after sailing. This would enhance the cultural heritage aspect further, and avoid leaving a colder analytical work, as warned against by Pujol and Champion (2012). Finally, our intent is to test these tools in a long-term study with a class of wayfinding students to determine the efficacy of its use in an educational setting, using previously established standards for measurement (Salzman, Dede, Loftin, & Chen, 1999).

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