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A high-tech, low-cost, Internet of Things surfboard fin for coastal citizen science, outreach, and education

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ABSTRACT

Coastal populations and hazards are escalating simultaneously, leading to an increased importance of coastal ocean observations. Many well-established observational techniques are expensive, require complex technical training, and offer little to no public engagement. Smartfin, an oceanographic sensor–equipped surfboard fin and citizen science program, was designed to alleviate these issues. Smartfins are typically used by surfers and paddlers in surf zone and nearshore regions where they can help fill gaps between other observational assets. Smartfin user groups can provide data-rich time-series in confined regions. Smartfin comprises temperature, motion, and wet/dry sensing, GPS location, and cellular data transmission capabilities for the near-real-time monitoring of coastal physics and environmental parameters. Smartfin's temperature sensor has an accuracy of 0.05 °C relative to a calibrated Sea-Bird temperature sensor. Data products for quantifying ocean physics from the motion sensor and additional sensors for water quality monitoring are in development. Over 300 Smartfins have been distributed around the world and have been in use for up to five years. The technology has been proven to be a useful scientific research tool in the coastal ocean—especially for observing spatiotemporal variability, validating remotely sensed data, and characterizing surface water depth profiles when combined with other tools—and the project has yielded promising results in terms of formal and informal education and community engagement in coastal health issues with broad international reach. In this article, we describe the technology, the citizen science project design, and the results in terms of natural and social science analyses. We also discuss progress toward our outreach, education, and scientific goals.

1. Introduction

Coastal areas are home to a large percentage of the world's population (Small and Nicholls, 2003), contribute significantly to the economy (OECD, 2016), and experience many of climate change's most dramatic impacts. Coastal hazards, including physical (e.g., severe storms and sunny-day flooding, sea level rise, salinization of groundwater, changing beach morphology, erosion, and marine heatwaves) and biogeochemical (e.g., ocean acidification, eutrophication, deoxygenation, harmful algal blooms, and pollution) issues are already having and will continue to have important consequences for coastal communities (Spalding et al., 2014). Furthermore, the spatial and temporal heterogeneity of coastal waters and these processes means that an abundance of observations are required to understand their dynamics for both scientific and operational/human safety objectives (Melet et al., 2020). New observational technologies are being rapidly developed to

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fill gaps in oceanographic datasets, but the nearshore/surf zone environment remains chronically under-sampled relative to its highly variable and dynamic nature.

Sea Surface Temperature (SST) has been deemed an Essential Ocean Variable by the Global Ocean Observing System (GOOS) due to its role in ecosystem health, extreme weather, and air–sea gas exchange, and because it acts as an indicator of surface and internal wave breaking, upwelling, rip currents, and fronts (Sloyan et al., 2019). *In situ* sensors provide high temporal resolution monitoring along coastlines but are typically sparsely deployed (10–100s of km) across large geographical regions within, for example, the US Integrated Ocean Observing System (IOOS). Furthermore, due to logistical challenges such as currents and breaking waves, *in situ* measurements in the surf zone are especially lacking.

Thermal infrared and microwave satellite remote sensing have made marked improvements in observing SST over wide spatial and temporal scales (Minnett et al., 2019). Operational monitoring and forecasting agencies routinely produce satellite maps of SST for use in climate forecasting and prediction systems (O'Carroll et al., 2019). These maps are calibrated and validated using a wide network of global *in situ* SST observations, collected from ships, buoys, and Argo floats. However, in coastal waters (particularly in the nearshore), calibration and validation activities are challenging, owing to the sparse number of *in situ* SST observations (relative to SST variability), the abundance of coastal aerosols that complicate atmospheric correction, and the contamination of the remotely sensed ocean signal by adjacent land (Brewin et al., 2018b).

Citizen science[2] can play an important role in filling gaps in *in situ* observations while simultaneously providing benefits for participants and communities (Schläppy et al., 2017). Surfers and other water sports recreationalists, people who already spend large amounts of time in coastal waters, can assist in the collection of data to fill in the aforementioned gaps through participation in citizen science projects (Brewin et al., 2017b; Sandahl and Tøttrup, 2020). For instance, initial studies using *in situ* data collected by surfers have suggested errors in satellite SST products at the coastline twice that of offshore regions (Brewin et al., 2017a). However, previous research with surfers (Brewin et al., 2017a) utilized off-the-shelf temperature sensors and GPS units and manual data merging, which would be difficult to scale.

Furthermore, citizen scientists can be much more than data collectors, and, in our experience, many participants are interested in water quality where they recreate. Consequently, they frequently recommend special projects based on their personal experiences (for example, monitoring projects near bleaching coral reefs, stormwater outfalls, and desalination plants). Environmental citizen science can contribute to environmental education and environmental literacy in the general public (Bonney et al., 2016). Surfing in particular is powerful in capturing interest across populations of both data collectors and other public audiences at, for instance, public lectures and community outreach events.

Here we describe the technological and programmatic design (see Methods) and current and prospective applications (see Results and Discussion) of a coastal citizen science project named Smartfin. Smartfin has complementary goals of improving the resolution of coastal observations to address critical scientific research questions linked to local and global environmental change while also improving ocean and climate literacy among participants and their communities. Since the participants are integral parts of the solutions to environmental change, their engagement in scientific monitoring may accelerate the pathway to finding and implementing potential solutions. Smartfin has been developed with scalability and ease-of-use as core principles. A participant only needs a surf or paddleboard, water access, and a charged Smartfin; all other aspects of datalogging, transfer, quality control, and visualization are automated and no modification of the surfboard or additional devices are required.

2. Methods

The Smartfin project comprises a coastal research endeavor, an oceanographic sensor-equipped surfboard fin, near-real-time data communications, a free and open data-driven web portal, education and student research opportunities, and an outreach and community-building effort (Fig. 1). Smartfin is intended for deployment on surfboards and paddleboards and was designed to automate all aspects of data collection, transmission, quality control, and data visualization, such that participants need only charge the rechargeable battery and immerse the device in natural waters (including fresh, brackish, and salt waters). A prior stack of Smartfin hardware, firmware, and software tools was described by Bresnahan et al. (2017); this article describes significant advances in engineering, coastal data collection and analysis, social science research, and efforts toward outreach and education.

The project's main components include: (1) technology research and development (these efforts are housed at Scripps Institution of Oceanography and Jacobs School of Engineering, UC San Diego); (2) program direction, manufacturing, and distribution (led by a 501(c)(3) nonprofit organization named Lost Bird Project); (3) deployment and data analysis (distributed across the globe, with primary contributors included as authors here and additional contributors cited where work has been published or is in progress); and (4) outreach and education, with a special focus on providing applied learning and student research opportunities (all project members). All contributors also participate in recommending improvements toward future iterations of the technology, new manufacturing and distribution strategies, and discussions regarding the direction of the project as a whole. In the following subsections, we focus on efforts toward (1) technological advancements and (2) design of the citizen science program, mutually aimed at improving the resolution of coastal observations and improving ocean and climate literacy among participants.

2.1. Technological capabilities

The Smartfin device (Fig. 2) is designed to collect temperature, position, and motion data from natural waters while matching performance specifications of a standard surfboard fin. Quantitative information regarding surf performance specifications (e.g., flex, durability) is challenging to obtain from the consumer surf industry; accordingly, performance is tested through trial and error in a variety of field and laboratory conditions, and fabrication methods are borrowed from advisors in the surf industry. Specifically, Smartfin electronics are sealed inside an epoxy resin (Resin Research or Entropy Resins) which is strengthened with a total of between eight to thirty layers of 6 oz fiberglass cloth (four to fifteen on each side of the electronics assembly—quantity depends on desired stiffness, which is a matter of both structural integrity and surfer preference). We pot fins using an injection molding process with either custom two-part silicone or aluminum molds, designed as the negative of the desired fin shape. The less expensive silicone molds are used during rapid prototyping while aluminum molds are used for higher volume production once designs are stable.

The components potted inside the Smartfin (Fig. 2, left) comprise three printed circuit boards (PCBs), a rechargeable 3.7 V 1.7 Ah Li-ion battery, a cellular antenna, and exposed stainless steel contacts for charging, programming, and wet/dry detection. The PCBs include (1) a Particle E-Series system on a module (microcontroller, power management, and cellular data transfer, utilizing both LTE and 2G/3G modem

[2] We note here that we use the common but disputed term "citizen science," intending to recognize public participation in science and engineering research by non-professionals and citizens of the world, but we acknowledge the problematic associations with the word "citizen," especially in the United States (Cooper et al., 2021; Eitzel et al., 2017).

Fig. 1. Smartfin's core components of coastal science, technology, open data, education and student research experiences, outreach, and community. Each component is described and illustrated in greater detail below.

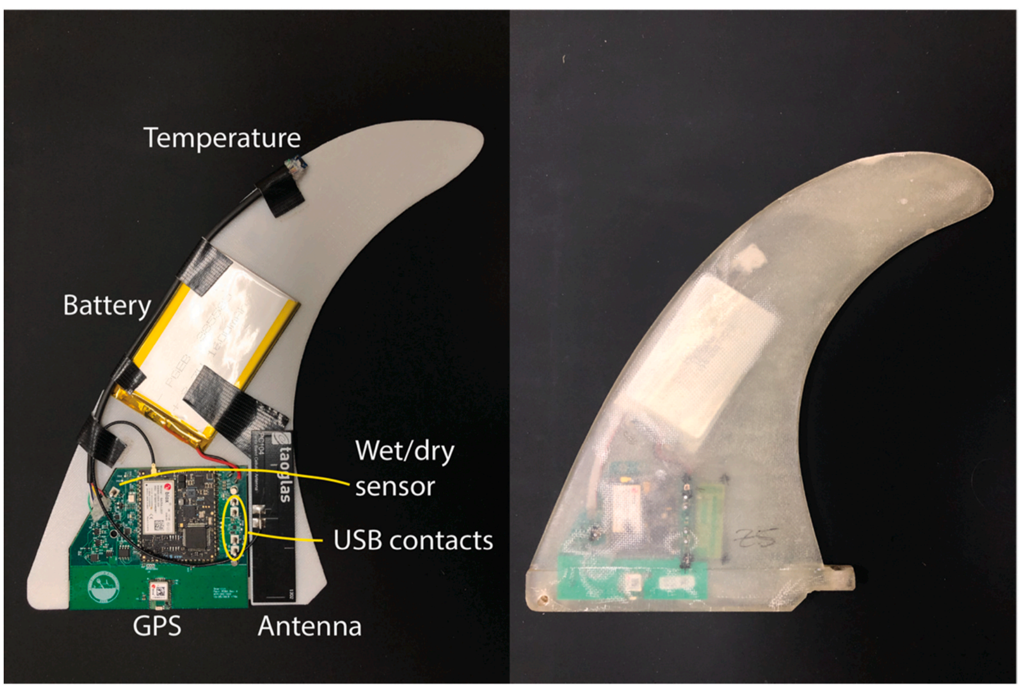

Fig. 2. Smartfin electronics assembly prior to (left) and after (right) potting in epoxy resin in a longboard fin shape. The fin-shaped device holding the parts in place in the image on the left is a custom 3-D printed jig designed to facilitate the potting process and create a repeatable design.

options), (2) a custom PCB for motion sensing (InvenSense ICM-20948), position (u-blox CAM-M8Q), data storage (Macronix MX25R3235F), wet/dry sensing (described in greater detail below), USB connectivity (via 316 stainless steel pins exposed to the environment), and (3) a temperature sensing break-out board. We refer to the custom PCB as "main" hereafter. The temperature board is connected to the main PCB via wires that allow the sensor (Maxim Integrated MAX31725) to be placed in a thinner part of the fin to improve thermal response time by minimizing the thickness of thermally insulating epoxy surrounding the sensor. USB and wet/dry sensor contacts are 2 mm diameter 316 stainless steel dowel rods which are soldered to the main PCB using LA-CO M-A stainless steel flux; they protrude through the fin's surface in order to contact the external environment (i.e., water or air) or charging cable. We have designed a custom charger to clip onto the fin and charge via the USB contacts. The cost of a Smartfin, including the PCBs, rechargeable battery, cellular antenna, stainless steel contacts, potting materials, charging cable, and cellular coverage is estimated to be $485 at low manufacturing volumes (tens per month). Advances in Smartfin technology beyond what is presented in Bresnahan et al. (2017) include: a wet/dry sensor for automated on/off functionality and in/out of water quality control, optimized GPS ground plane design for improved signal reception, automated cellular data transfer, USB connectivity, an upgraded motion sensor, and a web database with integrated quality control, programmatic data access via an API (application programming interface), map and time-series visualizations, and regional data selection tools.

The wet/dry sensor serves multiple purposes: (1) it turns the device on when entering the water and off when exiting and (2) it assists in quality control through providing definitive information regarding when the fin is submerged in water. The prior design (Bresnahan et al., 2017) lacked a hardware solution and required a more intensive post-processing quality control approach to remove out-of-water data during a surf session (see, for example, Brewin et al. (2020)). The wet/dry sensor is a comparator circuit which compares the resistance of environmental conditions (air or seawater resistivity, the inverse of conductivity) between two stainless steel dowel rods to the resistance of a PCB-mounted resistor. The dowel rods are spaced 59.5 mm apart for a conductivity cell constant of 18.9 mm^{-1} (or 1.89 cm^{-1}, using conductivity's conventional units). The sensor is designed to be activated above a conductivity threshold of 200 μS/cm, a typical minimum value for tap water. Due to the circuit's direct current design, some electrolysis and sensor corrosion occurs, but the sensor's duty cycle is <0.1% to mitigate this effect.

Data are logged at 1 Hz and a fully charged battery has the capacity for roughly 10 h of continuous sampling followed by cellular data transmission. A nominal surf session length is 1–3 h, so multiple sessions can be recorded before the battery needs to be recharged. Recorded data include: time (referenced to true time using the cellular modem and GPS timestamps), latitude, longitude, temperature, wet/dry status, and 9 degrees of freedom motion data (x, y, and z-axis-referenced acceleration, gyroscopic rotation, and magnetic heading). Temperature data are calibrated as described in Bresnahan et al. (2017) for an estimated accuracy of better than 0.05 °C relative to a Sea-Bird 37 CTD. Smartfin's temperature sensors have been shown not to drift through periodic checking of calibration coefficients; therefore, recalibration or user-calibration within the time frames of these tests (1 year) is unnecessary. Data are logged internally on the Smartfin's 4 MB flash memory throughout a surfing session (a 2-h session consumes roughly 100 KB) and, once the session has ended, the device attempts to connect to a cellular network. If the connection is successful, data are uploaded in base85-encoded data (encoding facilitates data compression, which is valuable for reducing cellular data demands). If the connection is initially unsuccessful, the device cycles through a low power sleep state and cellular transmission state. This cycle is repeated until either a connection is made or there have been five unsuccessful attempts at which point the device returns to its sleep state until it is plugged into the charging cable. We refer to data as being "near-real-time" due to the fact that, when a beach is near a cell tower, data are uploaded and available on the portal within minutes of the end of the session. GPS data, while logged at 1 Hz, are often not updated with valid data as frequently due to the device's inability to obtain a new fix while submerged in water (see Results and Discussion and Fig. 7 for more details). The GPS module (including its ceramic patch antenna) is located on the edge of the fin that is placed into the fin box which is consequently the closest part of the fin to the sky during normal deployments (shown on the bottom of Fig. 2, inverted during deployment).

Cellular data sent from the Smartfin device are decoded, stored, and visualized on a free, open, and interactive web portal (Fig. 3) built by Axiom Data Science using the tools they developed for the NOAA Integrated Ocean Observing System (IOOS) portals. Participants' identities are kept anonymous. The dashboard's features include hexagonal bins when zoomed out (i.e., average of all sessions within a given region, as depicted in Fig. 3, left), averages of individual sessions when zoomed in (Fig. 3, right), ability to draw polygons around areas of interest for additional visualizations and data download, and a time slider, as well as a number of aesthetic options for basemaps and colorbars. Moreover, the Axiom data integration will allow Smartfin to take advantage of the quality assessment algorithms developed for and standardized by IOOS (e.g., QARTOD or Quality Assurance/Quality Control of Real Time Oceanographic Data) (IOOS, 2016), which are already built into other Axiom-managed projects.

For data analysis and visualization in the present manuscript, we used Python 3.8 with pandas, numpy, matplotlib, and plotly modules and MATLAB 2019b. Mapped data use the cmocean thermal colormap (Thyng et al., 2016). Smartfin data were downloaded from a now-retired webserver at https://surf.smartfin.org and the modern server at https://stage.platforms.axds.co/. All data from the project's entire lifetime are freely available at the latter site with example download scripts at https://github.com/SUPScientist/Smartfin_data_via_Axiom_API. Scripps Pier temperature data were downloaded from https://sccoos.org/data-access/.

2.2. Citizen science program design

Over 300 Smartfin devices (including both the prior engineering design described by Bresnahan et al. (2017) and the design described here) have been distributed to participants through dozens of outreach and community-building events and through several dedicated scientific collaborations. Distribution and data collection began in 2016. To date, Smartfins have been distributed for free (made possible by philanthropic contributions), but they may be sold in the future in order to meet financial sustainability goals. Participants are primarily surfers and

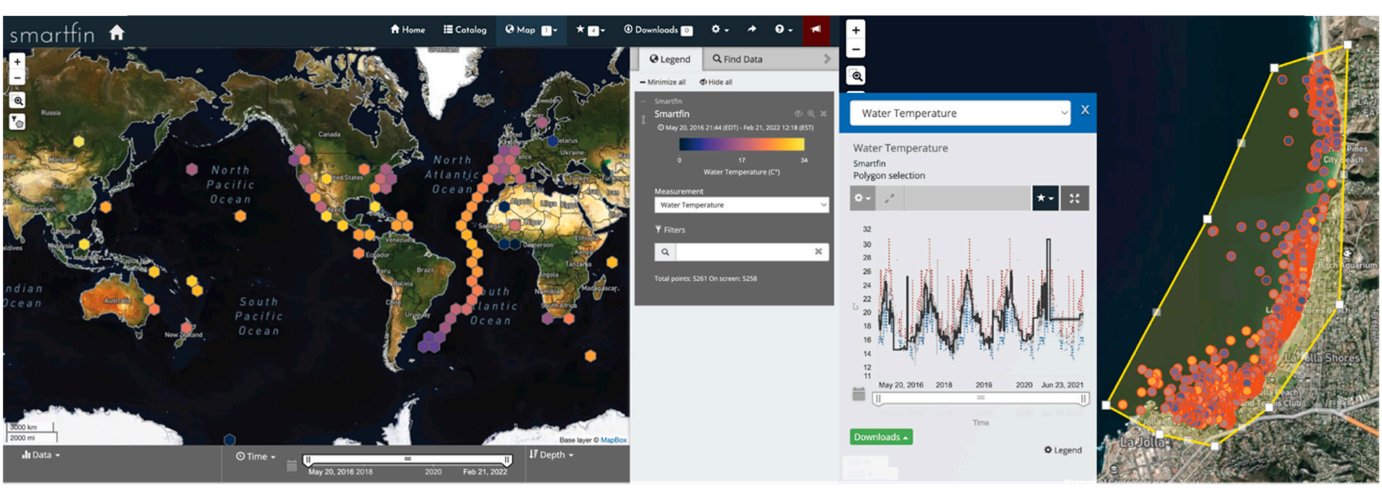

Fig. 3. Screenshots of Smartfin data dashboard, available at https://smartfin.axds.co. (Left) Global view (3159 sessions). Color within a hexagon represents the average temperature over all sessions within that region. The majority of data come from surf/paddle sessions; the transect through the middle of the Atlantic Ocean resulted from a research cruise, described in Brewin et al. (2021). (Right) Zoom into La Jolla, CA, USA, to illustrate the portal's additional mapping and time-series data views in the most densely sampled region (1119 sessions). Colored circles represent individual session averages. The time-series inset aggregates all data within the yellow polygon and illustrates the seasonal temperature cycle over the five years of the project. See Results for summary metrics of all data collected to date.

paddleboarders, but Smartfins have also been used on global class research vessels (Brewin et al., 2021), kayaks, and other small watercraft. As such, we use the general term "participant" to denote data collectors rather than categorizing everyone as a "surfer." Critically, data collection does not require any surfing or paddling capabilities but only access to natural waters. Participation in the program also includes data processing and additional outreach efforts on behalf of the project. Smartfin offers a unique advantage for adoption in citizen science programs in that the highly automated, Internet of Things connected devices make data collection easy without the need for complex, time-consuming, and technically challenging training, which can be a common barrier to participation (Frensley et al., 2017).

In the following Results and Discussion section, we highlight the extent of the data collection from the project to date, provide a summary of key results toward coastal scientific applications of the data, and describe the current extent of project education and outreach output.

3. Results and Discussion

3.1. Representative data

As of December 2021, 3159 Smartfin sessions (a total of 2768 h) have been recorded (each session is defined as any length of time that a participant submerges the device, from several minutes to several hours). While data collection has occurred relatively infrequently in many of the locations shown in Fig. 3 (often only one session within a given hexagon), several locations have substantially longer and fuller time-series. For instance, La Jolla, CA, USA—the location of the first pilot study and home of the engineering efforts—has a rich data record comprising 1119 sessions (1197 h), or roughly $1/3^{rd}$ of the total dataset (data extracted from polygon in Fig. 3, right panel).

Smartfin time-series data include temperature, motion (x, y, and z-axis acceleration, rotation, and heading), time, and location. Temperature and vertical accelerations are the two primary variables used in coastal analyses. Fig. 4 illustrates representative data records over a ~60-min recording session. The thermal response time is evident at the beginning and end of the session where the Smartfin undergoes sudden temperature changes when moved from air to water. A 63% response (t_{63}) is reached in roughly 30 s; efforts are underway to improve the thermal response time in order to make the device more valuable in applications where a faster response could help elucidate smaller scale patterns. After removing the first and last 150 s of the session ($5*t_{63}$ = 150 s, for a 99% response), the temperature range of the session is 0.8 °C (Fig. 4). Shorter term variability (10s–100s of seconds) is on the order of several tenths of a degree, indicative of the temporal scale of observable dynamics (noting that the surfer is also moving during this time). Vertical accelerations (along the z-axis, or normal to the relatively flat surface of the surfboard) are due to both surfer motion and local wave activity. Vertical acceleration is mostly stable around a baseline of 1 g (that is, the accelerometer is recording the Earth's gravity), with small, ~0.1 g variations corresponding to wave activity and small motions from the surfer and larger spikes of ~1 g corresponding to the acceleration from surfing waves (Fig. 4). The mapped image (Fig. 4, right) shows the spatiotemporal variability in temperature over the area and time covered by the surfer.

3.2. Ongoing and future applications of Smartfin data for coastal research

Smartfin data are being analyzed in and proposed for a number of promising applications. Fig. 5 depicts several of the spatial and temporal scales over which Smartfin data are useful. In a temporal sense (Fig. 5A and B), Smartfin data within a defined region can provide a time-series comparable to that from moored instruments. The data can be used both (1) to highlight dynamics not readily observable by fixed instrumentation (especially where instruments may be in variable water depths due to tides and wind waves) and (2) to provide a time-series where there are no moored instruments. Smartfin can also provide spatially (Fig. 5D) and spatiotemporally (Fig. 5C) resolved data to illustrate variability within a given region.

Smartfin temperature data have proven valuable in remote sensing validation studies in the coastal zone where *in situ* observations are especially sparse relative to their variability and where interferences from adjacent land with remotely sensed ocean signals are strong. Comparisons over a large SST gradient between SST collected using a Smartfin and that collected using a ship-mounted Infrared SST Autonomous Radiometer (ISAR), a state-of-the-art instrument used for satellite validation, showed mean differences <0.1 °C (Brewin et al., 2021), comparable with intercomparisons of different infrared radiometers (Barton et al., 2004). Smartfin data are now being used for evaluating the next generation of satellite thermal sensors, for example, the European Space Agency (ESA) Sea and Land Surface Temperature Radiometer (SLSTR), onboard the Sentinel-3 satellite (Brewin et al., 2018a).

A particularly exciting avenue of research is the use of Smartfin data for evaluating very high-resolution satellite thermal data (<100 m pixels). Initial work has looked at agreement between high-resolution SST data from the Advanced Spaceborne Thermal Emission and

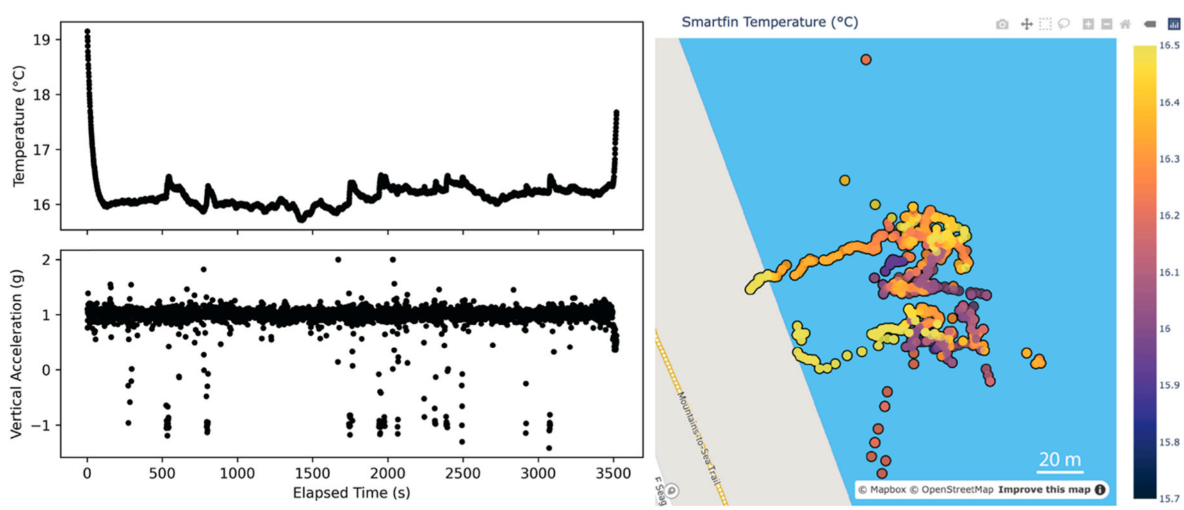

Fig. 4. Representative Smartfin data from a single 1-h session in Nags Head, NC, USA, on 23-Nov-2020. (Left) Smartfin temperature and acceleration in the vertical (normal-to-board) dimension. Other motion sensor data (e.g., accelerations in the other two dimensions and rotations/headings in all three dimensions) are not shown in order to improve clarity. (Right) Smartfin temperature data from the same session, mapped using the integrated GPS.

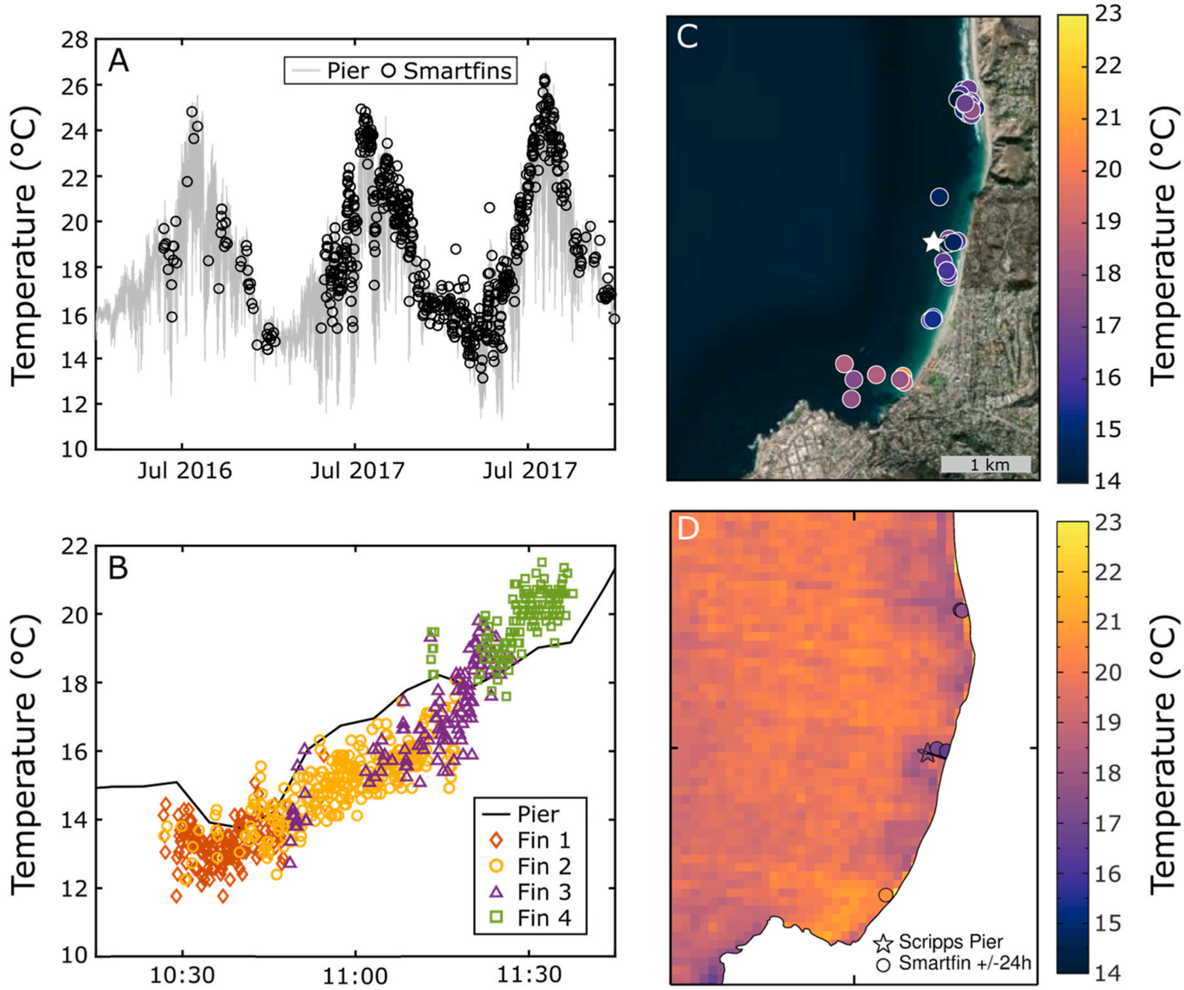

Fig. 5. Data from the Smartfin program representing the potential for scientific uses across different spatial and temporal scales. A) Temperature data from Smartfin and the Scripps Pier (https://sccoos.org/autoss/) demonstrate how multiple Smartfin sessions from one region can be used to create a multi-year time series. Each Smartfin datapoint is the average data from an individual surf session plotted at the midpoint of the session's deployment time (665 sessions). Data from Scripps Pier is measured at a nominal depth of 5 m MLLW and recorded every 4 min. All surf sessions were within 7 km of Scripps Pier. B) A zoomed in version of panel A demonstrating the potential of deploying multiple Smartfins at any given time. Here, four Smartfins were surfed near Scripps Pier on June 13, 2016. Unlike in panel A, Smartfin temperature data are the instantaneous, high frequency measurements throughout each surf session. C) The average temperature (as in panel A) of each Smartfin surf session during the month of April 2018, plotted spatially (49 sessions). D) SST derived from an ASTER satellite pass on April 10, 2018, using the algorithm of Matsuoka et al. (2011), with the average session temperature of Smartfins that collected data within ±24 h of the satellite data overlaid on top (n = 5 sessions). In panels C and D, the star represents the location of Scripps Pier and circles are individual Smartfin sessions.

Reflection Radiometer (ASTER), onboard the MODIS-Terra satellite, and processed using the method of Matsuoka et al. (2011). Preliminary comparisons have indicated good agreement (mean difference = 0.39 °C, for 7 matchups, ±24 h), with complex nearshore SST dynamics seen in both ASTER and Smartfin data (see Fig. 5D). Complementary efforts are also being made to improve SST products derived from thermal bands of the Landsat sensors (Vanhellemont, 2020a). In a recent study, Vanhellemont et al. (2021) used Smartfin observations to validate very high-resolution nearshore SST products derived from Landsat 8/TIRS. They showed significant improvements in the new reprocessing of Level 1 Landsat 8/TIRS data (Collection 2) with the Thermal Atmospheric Correction Tool (Vanhellemont, 2020a, b), providing SST products in better agreement with Smartfin when compared with standard USGS Collection 2 Level 2 processing. Following the recent launch of Landsat 9, Smartfin data is expected to continue providing critical *in situ* observations for satellite validation activities and supporting the use of high-resolution satellite SST products for operational applications. In these applications, we typically examine a 3 × 3 grid of satellite pixels surrounding the Smartfin's location.

We have also been collaborating with physical ocean modelers who have been using Smartfin data to evaluate simulations of nearshore temperature dynamics using high-resolution ocean models (e.g., https://plymouthmarineforecasts.org/, based on the Finite Volume Community Ocean Model, FVCOM; *pers. comm.*, Dr. Michael Bedington, Plymouth Marine Laboratory, UK). Smartfin data have been used to look at the relationship between temperature and nearshore phytoplankton abundance, helping to understand seasonal changes in how phytoplankton are controlled by resources in nearshore waters (McCluskey, 2021; McCluskey et al., 2022). Additional pilot work examined how the uptake of Smartfin by the surf community could contribute to the efforts toward global monitoring of surf zone physical data (*pers. comm.*, Dr. Kylie Scales and Dr. Javier Leon, University of the Sunshine Coast, Queensland, Australia).

We are also investigating processing approaches and applications of the motion sensor data (accelerations, rotations, and headings). Motion sensor data are processed through a combination of supervised machine learning (for classification of surfing behaviors into categories including paddling, wave riding, and waiting for waves) and standard wave statistical approaches (following, for example, Lawrence et al. (2012) and Longuet-Higgins et al. (1963)) to quantify wave activity (Simmons, 2019). Continued efforts are underway to double-integrate vertical accelerations and compare results with a frequency domain analysis for the estimation of wave-induced displacements. Results from this work may prove challenging to interpret due to the variable buoyancy of surfboards and other deployment platforms and the surfers' own weight and motions. However, preliminary results (Simmons, 2019) indicate that this metric could be valuable in certain coastal applications and for improved user engagement (for example, to provide the participant with certain metrics of wave characteristics from their sessions).

The wet/dry sensor has been proposed for use as a direct current conductivity sensor, but the circuitry required to add this functionality slows the sensor's response time substantially, requiring it to be on longer (and therefore corroding more). Conductivity sensors typically use alternating current for this reason and to reduce electric field effects for improved accuracy; consequently, we have chosen not to pursue conductivity sensing with this circuit. However, we intend to integrate a seawater conductivity sensor in the future.

Additional proposed and ongoing activities in the natural sciences include groundwater intrusion monitoring (J. Scopa, MS thesis, in progress), coral bleaching assessment, integration of additional water quality sensors (G. Schmid, NSF REU, 2019; based on work by Bresnahan et al. (2016)), and improvement of Smartfin system design and data analysis (Engineers for Exploration NSF REU Site and UCSD student organization, ongoing). There are many exciting applications for highly distributed, citizen science–based sensing of nearshore water quality, including the potential expansion of the previously described satellite validation activities into the domain of ocean color remote sensing (with, for instance, *in situ* fluorometers and turbidimeters). Smartfin's near-real-time data transmission capabilities will prove especially valuable with the integration of other ocean and human health and safety sensing capabilities. Finally, we propose to use geolocation data to quantify changes to wave characteristics induced by, for example, sea level rise, beach renourishment, and hard stabilization of the coast. Related research seeks to study surfers' perceptions of changing beach conditions (e.g., Usher (2021)); once collected at higher volumes, Smartfin's GPS data could augment such analyses.

3.3. Results in education, outreach, and citizen science

Toward our education and outreach goals, we have participated in several hundred in-person events (prior to the COVID-19 pandemic) and interviews, including written and live news and pop culture stories, podcasts, and public radio broadcasts, for example, in nations including the US, UK, Canada, Australia, and Japan, demonstrating the project's potential for science communication. We list some of our most notable public outreach opportunities with especially broad reach in Table 1.

Additionally, our team and collaborators have conducted social and economic studies on the participants themselves (Johansson, 2019; Scott, 2019) in order to better understand motivators for participation and willingness to pay for hardware. Several dozen student researchers have been involved in the project (especially data analysis and engineering roles), providing excellent applied educational opportunities (e.g., roughly twenty undergraduate students through the NSF Engineers for Exploration REU site and UC San Diego student organization; Simmons undergraduate honor's thesis; Johannson, Scott, and McCluskey master's theses; Scopa master's thesis in progress; Schmid and Connors CCE-LTER REUs). Smartfin has been used in both informal (i.e., guest lectures) and formal (i.e., part of curriculum and taught by main instructor) educational settings in several universities and high schools. We are also striving to expand our efforts toward engaging and attracting interest in STEM from typically underrepresented student populations, with the ultimate goal of increasing inclusion and diversity in science. For example, we deployed Smartfins with students from Ocean Discovery Institute in Mission Bay, San Diego, CA, USA, and reviewed the results together. Surfing is not typically thought of as a sport that attracts diverse populations, but broadening participation has been a central goal in recent Smartfin proposals.

Table 1
Select press and public outreach examples.

Outlet	Event or Publication Name	URL
Science Magazine	Scientists put a 'smartfin' on my surfboard. Is it the next wave in ocean monitoring?	https://www.science.org/content/article/scientists-put-smartfin-my-surfboard-it-next-wave-ocean-monitoring
Surfer Magazine	Smartfin Turns Surfers Into Citizen-Scientists	https://www.surfer.com/features/smartfin-turns-surfers-into-citizen-scientists/
National Public Radio's All Things Considered	Surfing For Science: A New Way To Gather Data For Ocean And Coastal Research	https://www.npr.org/2018/07/16/629588460/surfing-for-science-a-new-way-to-gather-data-for-ocean-and-coastal-research
South by Southwest 2019	Smart Oceans: Tech from Surf to Seafloor	https://soundcloud.com/officialsxsw/sxsw-2019-smart-oceans-tech-from-surf-to-seafloor
TEDxTruro	Can Outdoor Recreation Help Manage Environmental Change?	https://www.ted.com/talks/bob_brewin_can_outdoor_recreation_help_manage_environmental_change
Scientific American	Surfing for Science: Ocean Enthusiasts Could Help Gauge Coastal Warming	https://www.scientificamerican.com/article/surfing-for-science-ocean-enthusiasts-could-help-gauge-coastal-warming1/
Euronews	Surfing scientists and algae hunters use Sentinel-3 to study coastline	https://www.euronews.com/2018/04/19/sentinel-ocean
Creative Mornings San Diego	The Science of Community	https://creativemornings.com/talks/phil-bresnahan
BBC Earth Unplugged	How Surfers Help Scientists Study the Ocean	https://www.youtube.com/watch?v=CU-IX8tqP_4
Forbes	How Surfboards and IoT Are Making Waves In Climate Change Research	https://www.forbes.com/sites/delltechnologies/2017/11/22/how-surfboards-and-iot-are-making-waves-in-climate-change-research/?sh=5344f46c27e1
Seeker	Waves Can Tell Us A Lot About Climate Change, But You Have to Catch Them First	https://www.youtube.com/watch?v=toeoYNQNZgA
Great Big Story	The Surfboard Fin That's Saving the Ocean	https://www.youtube.com/watch?v=LEuPBV2L4IQ

3.4. Limitations and proposed improvements

We also acknowledge several limitations of Smartfin. First, citizen science data, especially from surfers, are biased in time and space. The vast majority of data collection will occur during the day, during favorable weather/wave conditions, and only at select locations. Importantly, however, an analysis of a century-long record of manually collected SST at the Scripps Pier, La Jolla, CA, USA, and a decade-long record of autonomous SST data suggests that random daytime sampling may still capture much of the temporal variability (Rasmussen et al., 2020). Additionally, it would be desirable to have alternatives to cellular communication for data upload; progress toward a USB interface is underway. A prior version of Smartfin (Bresnahan et al., 2017) used Bluetooth Classic and custom mobile applications for both iOS and Android devices. A pilot test of this version indicated that individuals frequently collected data but did not upload it via the application to the Smartfin servers, stating frustrations with the additional effort, including time required, to transfer data from the fin to the mobile device. Removing as many barriers to participation as possible is key in citizen science, as participants are typically volunteering to collect data and may not have the time or training to overcome such barriers (Frensley et al., 2017). Moreover, cellular technology lends itself to near-real-time applications and we have envisioned potential applications in both public health/safety (e.g., wave size or rip current alerts, potentially water quality in future iterations) and consumer products (e.g., water temperature, which is a product already supplied by Surfline based on sparse observational data). These advantages of cellular data transfer notwithstanding, there are many situations in which an alternative (e.g., USB or Bluetooth Low Energy) would be desirable, such as when participants are outside of cell service and for improvements in energy usage on the device.

A second area for technical improvement is the adaptability of the Smartfin to other watercraft. The current design is suited for longboard surfboards and stand-up paddleboards. The component into which the Smartfin mates, the surfboard's center fin box, is a widely available and inexpensive product (e.g., https://www.finsunlimited.com/surf-channels/105-surf-channel), rendering conversion for other platforms a relatively straightforward undertaking (Fig. 6). Nonetheless, the Smartfin project could rapidly expand usage through the development and supply of additional form factors. The current outline of the Smartfin is one intended for usage primarily on surfing longboards or paddleboards, though prior versions of the Smartfin have been intended for shortboards. Larger and typically more buoyant boards offer two advantages due to their position floating on top of the water: (1) the depth of the measurements is simpler to estimate (given the absence of a pressure sensor) and (2) since water is opaque to GPS signals, a board and fin closer to the surface will return more GPS fixes (Fig. 7). For reference, performance shortboards are typically <30 L, longboards are 50–70 L, and stand-up paddleboards are in the 100–300 L volume range. Recent modifications to the GPS ground plane on the Smartfin PCB have led to substantial improvements in GPS fix rates beyond what is depicted in Fig. 7, but this effect has not yet been rigorously quantified. The expectation is that the most buoyant watercraft should return close to 100% of the potential GPS data, with diminishing returns as buoyancy decreases.

An opportunity for improvement with joint programmatic and technical aspects is in the gamification of participation in Smartfin, and in the integration/improvement of other app-based features aimed at enhanced engagement. Other citizen science (and countless commercial) projects have found success in gamification (Bowser et al., 2013), with approaches including, for example, the dissemination of metrics related to participation rates. We anticipate that the inclusion of the aforementioned wave metrics and higher GPS fix rates will be especially valuable to this user group. Relatedly, the current data infrastructure (https://smartfin.axds.co) was built by and for oceanographers, not for participants; improving data visualizations with the end-user in mind could yield substantial gains in participation rates. Indeed, centering participants in all aspects of project design has proven beneficial in comparable citizen science endeavors (Bonney et al., 2016). Furthermore, current and potential participants regularly request both improved access to new devices and to scientific uses and outcomes from their data and participation. We are also striving to improve engagement and educational offerings through, for instance, blog posts about specific applications of the data (see, for example, https://smartfin.org/2018/10/amt28/).

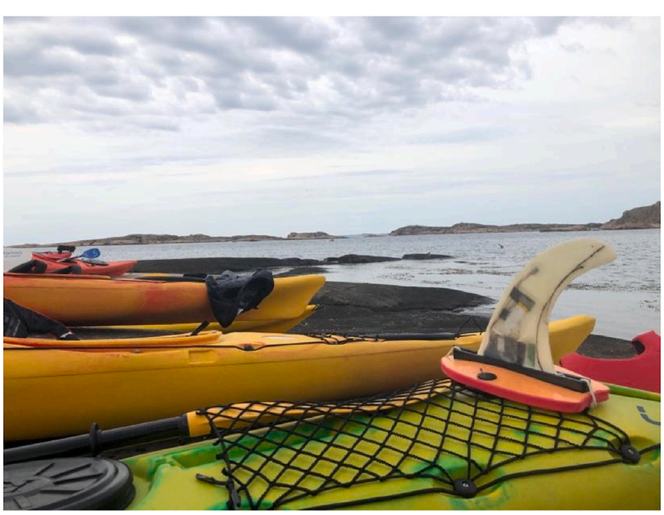

Fig. 6. Adaptation of the Smartfin for other watercraft (in this case, a sea kayak) by the fastening of a surf fin box to a small flotation device which is towed behind with a rope.

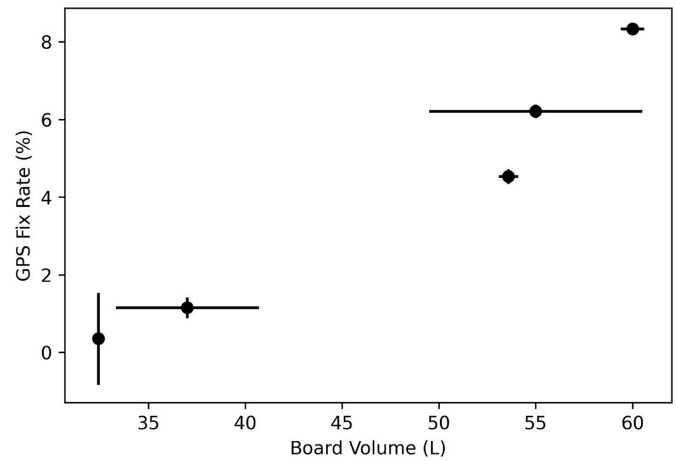

Fig. 7. Frequency of GPS fixes on Smartfin vs. surfboard volume. Board volumes are taken from manufacturer's website when available and estimated from length, width, and thickness when not otherwise published. Horizontal error bars depict uncertainty in board volume, estimated as 10% for boards without manufacturer-published volumes and 1% for boards with published volumes. Vertical error bars show the coefficient of variation, or standard deviation divided by mean, of each board's fix rate over all sessions. This analysis comprises 31 Smartfin sessions with approximately five sessions each ($n = 5$) for the six boards depicted here.

4. Conclusion

The Smartfin project has proven to be a powerful way to combine the collection of coastal physical data with a citizen science project geared toward public participation in data collection, public outreach, and informal education. The Smartfin device is an effective tool for automated, Internet of Things citizen science coastal monitoring with features including high accuracy temperature sensing, motion and position recording, automated on/off and cellular transmission capabilities, and near-real-time, free, and open data visualizations and download in standard scientific data formats. Recent projects have demonstrated the capabilities of the temperature sensor in filling gaps in nearshore monitoring for the improvement of time-series observations and satellite validation. Ongoing and future work will build on these efforts and make contributions to new avenues of ecosystem modeling and high spatial resolution wave and water quality monitoring. Smartfin is especially valuable in the dynamic surf zone where instrument deployments can be very challenging. Additionally, social science research has contributed to our understanding of motivators and barriers to participation.

Furthermore, through the increased manufacturing, distribution, and use of the technology, we anticipate that the dataset will become increasingly valuable. Currently, it is not feasible to use Smartfin data for real-time operational needs due to the unpredictability of data collected by citizen science participants, but as concentrations of devices increase in a given region, it will become likelier that the dataset will contain recent uploads from a region of interest. Importantly, Smartfin can contribute valuable SST measurements in the nearshore region for a fraction of the cost of many alternative technologies, especially when instrument deployment and servicing costs are taken into account. Many other technologies are capable of providing data of comparable quality, but few provide similar opportunities for public participation in coastal oceanographic research. Finally, Smartfin's broad public engagement demonstrates its capacity to reach large audiences with ocean and climate information and a captivating message.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Philip Bresnahan reports financial support was provided by San Diego Gas and Electric Co. Andrew Stern has patent #US10384749B2 issued to Andrew Stern.

Data availability

All data are freely available at the open data portal sites referenced in the article

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