Demonstrating ReefSense: Leveraging water properties to create computational, climate-adaptive, artificial reefs

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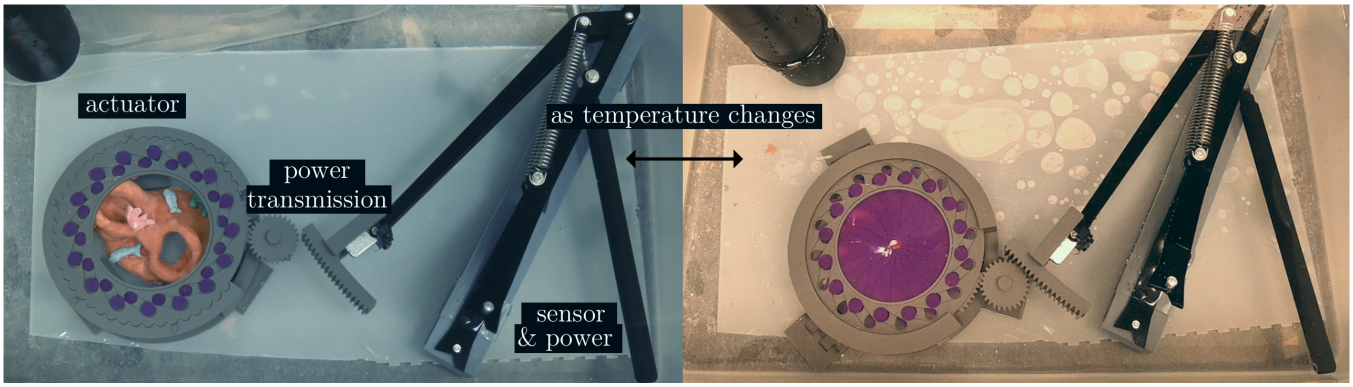

Figure 1: ReefSense passively shades an artificial coral reef when temperatures are too high

Abstract

Corals are endangered from climate change, due to exposure to sunlight during times of especially high water temperature. However, constantly shading corals also harms them. We thus introduce ReefSense: a passive computational system that can help shade corals using the energy of the ocean to sense and actuate. We have prototyped and tested ReefSense setups with 3D printed– and off-the-shelf components: the key aspect is that the system uses the energy of temperature change and water flow to deploy shade when it is needed. We discuss ReefSense, a bachelor thesis project, as a point in a more general space of computation that can work with nature instead of against it, and allow future computational systems to integrate more tightly with the world.

CCS Concepts

• **Human-centered computing → Interactive systems and tools**; • **Applied computing → Computer-aided design**; • **Social and professional topics →** *Sustainability*.

Keywords

unconventional computing, digital fabrication, non-electronic computing, coral reefs, sustainability

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1 Introduction

Today's computers power impressive general-purpose systems, but have a high cost to create (in terms of extractive ecosystem damage) as well as to operate (requiring electrical energy). Unconventional computers, on the other hand, can be created from natural components and run on natural power. This uniquely suits deployment in remote, fragile ecosystems.

One such ecosystem is coral reefs. Corals can only tolerate a certain level of thermal stress before they bleach, i.e. they expel the symbiotic algae they depend on for food production through photosynthesis [9]. Irradiance during high-temperature events can compound the damage [2]. This combination of high water temperature and high light exposure is especially problematic for shallow-water, coastal corals [2], those on which millions of people depend on for their livelihoods and diet [21].

We target these corals with ReefSense: a system integrating temperature-responsive actuation into artificial reefs, aiming to shade corals in periods of thermal stress. Our proposed system has three components: sensing temperature increase, harvesting power, and shading/un-shading the corals. We discuss prototypes of these three sub-systems: a collection of 3D printed and off-the-shelf components.

ReefSense is intended to be integrated in 3D printable artificial reefs [13, 15]. It is electronics-free, powered by water movement, air pressure, and material expansion that interact through specific geometric structures. Computation is purely geometric, resulting in a (theoretically) fully printable system. ReefSense is thus a low-tech, cheap, and low-impact alternative to advanced technologies [7, 29].

ReefSense demonstrates a novel form of computation that addresses a severe and urgent crisis: with a 2 °C global warming, 99% of corals are predicted to die [5]. Beyond ReefSense's prototypes, we also discuss the further work required for ocean deployment and envision how our designed components can be extended to other applications.

2 Related Work

ReefSense builds off ideas about protecting coral reefs, as well as work in designing non-electronic computation and WaterHCI.

Scientists have discovered ways to mitigate bleaching, targeting one of two contributors: sunlight (through e.g., shading [2] or scattering [29]) or temperature (especially through upwelling cool water from the deep ocean [7]). We focus on shading with ReefSense, as it requires relatively less energy.

Electronics-free computation offers various freedoms, and has been an active area of research and development for 1000s of years. With ReefSense, we use flueric computation concepts [18, 26] combined with computation through materials' behaviours when exposed to heat [31–33] and mechanical force transmission [11].

While prior work has deployed playful interactions with water [8, 24, 25], it has also bemoaned the need to waterproof electronics to enable WaterHCI interaction without endangering computing systems [22]. Importantly, ReefSense does not require waterproofing, as it is electronics-free. Additonally, ReefSense's sensing and actuation actually *take advantage of* water properties to achieve sensing and actuation, rather than seeing water as a disadvantage.

3 ReefSense

3.1 Physics and Mechanics

Building a system that is to be deployed in water brings many requirements that differ from building systems that should work in air related to its structure and materials. It also brings opportunities for sensing: because material properties change with temperature, it is possible to sense the heating ocean passively.

3.1.1 Density. At sea level, water is between 770 and 890 times as dense as air [3]: a much larger weight will be exerted on a system deployed in water than in air. Consequently, structural integrity is important to withstand pressure. As the corals most susceptible to bleaching live in shallow areas (< 5 m deep) [2], we fortunately only need to target some additional weight.

3.1.2 Buoyancy. Water's density means that submerged objects will be subjected to buoyancy [3]. To prototype in PLA, we therefore use high infill percentages to enable our object to sink, as PLA has barely more density than water (see Table 1 [6]).

Table 1: Densities of different materials and mediums. PLA from Emiliano [6], all other values from Denny [3]. Air, fresh water, and sea water reported at 20 °C

Medium	Density, ρ (kg m^{-3})
Air	1.205
Fresh water	998.23
Sea water (3.5% salt)	1024.76
PLA	1240
Coral skeleton	2000

3.1.3 Temperature-dependent material properties. Water's density decreases as temperature increases. The Galilean thermometer relies on this principle (Figure 3), including objects of varying densities and observing how they sink or float. The ReefSense sensor also relies on temperature-dependent floating to release gates and open new areas of the structure.

Phase change materials can store and release thermal energy during the process of melting and solidifying [30]. Among many other uses, phase change materials are used in wax motors, which use thermal expansion to achieve a pushing force [12]. In some of our prototypes, we leverage a wax motor as both sensor and power source.

3.2 Prototype Systems

To create an artificial reef that responds to changing water temperature by creating shade, we require:

(1) A power source or harvester
(2) A temperature sensor
(3) A method of power transmission
(4) An actuator

Specifically, we need the system to keep the reef unshaded when temperature is below a threshold (the *off state*) and to shade the reef when temperature is above a threshold (the *on state*).

We explored different approaches and made prototypes with focus on implementation [10]. All of our 3D printed prototypes are printed on a Bambu Lab X1-Carbon printer with Bambu Lab PLA Basic 1.75 mm. For all prints, we have printed with 0.2 mm layer height. For initial prototypes we used 15% infill density to quickly ensure structural function, and later increased to 85-100% to ensure the printed objects sink in water.

We have so far prototyped two major system designs: System 1 relies on water flow released by a Galilean thermometer to generate energy via a waterwheel and mechanically deploy a shade. System 2 uses the expansion of a wax motor to sense temperature change and generate kinetic energy directly.

3.2.1 System 1. System 1 (see Figure 2) uses pressurized water flow as a power source. The water flow is unlocked through a Galilean thermometer sensor with one marker that triggers at ≈30 °C, which between the on and off states toggles a pinch valve to allow water flow. The water moves through the system in 5 mm diameter plastic tubes, and a waterwheel and gearing system create actuation. Shading is achieved through a hand-fan-like mechanism.

Table 2: Summary of two different approaches to ReefSense. PS = Power source. PT = Power transmission.

Component	System 1	System 2
PS	Pressurized water	Wax motor
Sensor	Galilean thermoscope	Integrated in wax motor
PT	Gears and water flow	Gears
Actuator	Opens "hand fan" shade	Opens "camera shutter" shade

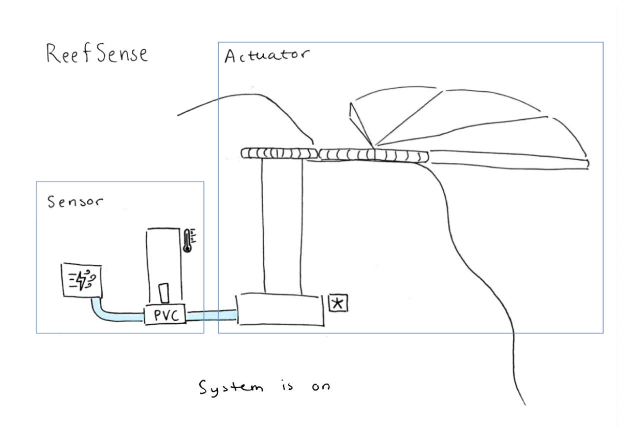


Figure 2: An overview of System 1 in on state

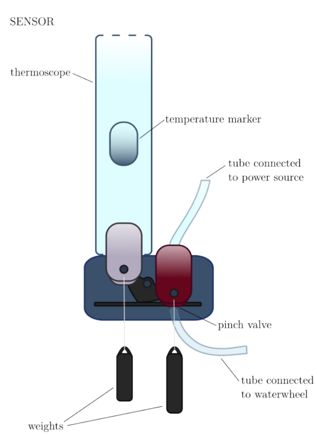


Figure 3: Illustration of the Galilean thermoscope sensor

We have initial prototypes of the components of System 1, but did not integrate them into an end-to-end system. Sketches are shown in Figures 2 and 3, and photos of the sub-parts are in the Evaluation section.

3.2.2 System 2. System 2 uses a wax motor as both power source and temperature sensor. As temperature increases, the wax inside the wax motor melts and expands, which causes an arm to move. A gear is attached to the end of the arm, and as the arm reaches a specific rotation (in degrees), this gear moves past a second gear attached to a camera-shutter-like shade, which then opens. As the temperature drops, the arm will move back, closing the shade. This system has been fully achieved through prototypes, which are shown in Figure 4.

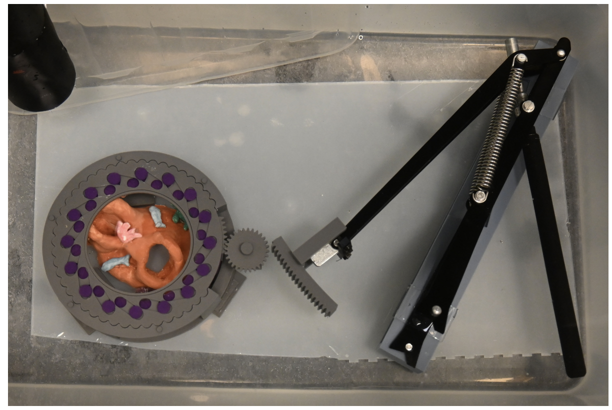


Figure 4: System 2 in off state

Our System 2 prototype uses a non-electronic automatic window opener [1], intended to regulate temperature in greenhouses. It consists of a wax-based temperature sensor and two arms. We fixate one arm to a 3D printed stand, thus only the other arm moves as temperature increases. To the moving arm, we have attached a 3D printed slider with a partial spur gear. The proportion of the gear that is present controls the temperature at which the next component is actuated; we use a 20 °(/360) gear. When the arm rotates, the spur gear passes by a gear system mounted on the shade, which then opens.

4 Evaluation

We have explored various designs for each component of ReefSense and evaluated the components both individually and as part of their respective full systems through experimental validation [14]. Experiments are summarized in Table 3.

5 Discussion And Future Work

ReefSense suggests interesting possibilities for the future of artificial reefs that go beyond merely hosting corals to measure and compute. Below, we discuss next steps in our prototypes, as well as the open-ended potential of the concept.

5.1 Deployments for in-ocean reefs

So far, we have evaluated ReefSense in a plastic box, using tap water. In-ocean deployment brings additional challenges and opportunities.

In particular, our next steps include using nature-appropriate materials. PLA is both bio-based—based on plant starch [28]—and biodegradable, but degrades slowly in water [1]. This means the system will last longer before degrading, but if parts break off, the plastic persists and possibly interferes with ocean life. We are exploring using our clay 3D printer with terracotta—often used in artificial reefs [15] to encourage the settlement of coral larvae—or

[1] purchased at www.silvan.dk

Table 3: Summary of experiments performed to evaluate ReefSense. (1) refers to System 1 and (2) to System 2

Experiment	Setup	Results	Comment
Temp. sensitivity (1)	We submerged a weighted water bottle in water, heating up the water, and observing when it sinks (see Figure 5)	The bottle sank after a 7.9 °C increase	Improved sensitivity could be achieved with a larger temperature marker
Temp. sensitivity (2)	We submerged the system in water, heating up the water, and observing the temperature at which opening of the shade starts and is completed (see Figure 9)	The shade started opening at 26.1 °C and was fully opened at 27.0 °C	How fast the shade opens depends on gear sizes
Torque required (1)	We rotated the shade mechanically by pulling with a spring scale, measuring the required force in and out of water (see Figure 6)	0.458Nm force required above water; 0.553Nm below water, i.e. submersion creates a 20.7% increase	In both cases the force is relatively small; hydrodynamics could be improved with thinner wings with sharper edges
Torque required (2)			Remains to be evaluated
Water pressure loss (1)	We applied power using a bottle with water at different points in the system, observing whether actuation occurs (see Figure 7)	With the pinch valve controller, we cannot drive the waterwheel. Removing it, we can	Significant water loss suggests new approaches are needed in future prototypes
Full system (1)	We applied power using a bottle with water to the full system (above water without the pinch valve controller) (see Figure 8)	Still insufficient water pressure to open shade	Higher-pressure power source needed
Full system (2)	We tested the full system underwater using two shade sizes, heating/cooling the water, and observing actuation (see Figure 9)	Both prototypes opened with temperature increase and closed (partly) with temperature decrease	The shade didn't close entirely in some repetitions due to difficulty placing sensor relative to actuator

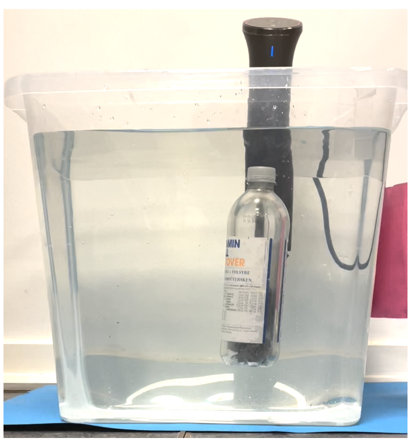


Figure 5: Setup for determining the required weight of the temperature marker and the temperature sensitivity of the thermoscope (System 1).

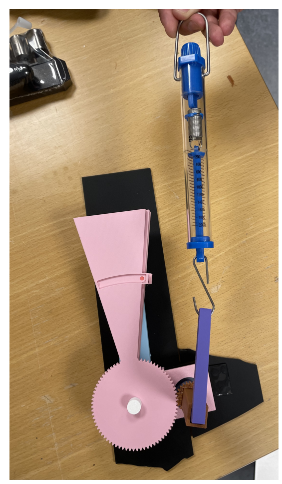
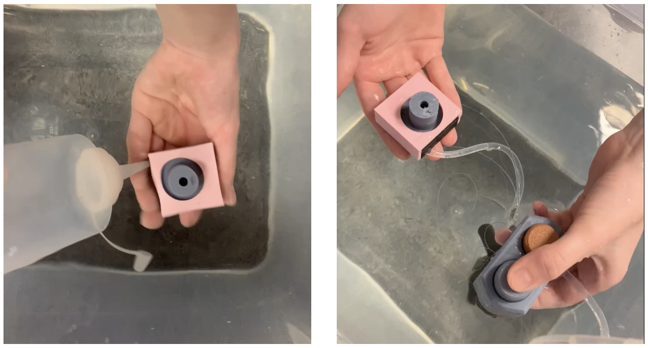


Figure 6: Setup for evaluating required torque (System 1)

bioconcrete made from seashells [13]. Some of our prototype components are not currently printed, and will require special material consideration [16]. 3D printing in other materials will impact our systems' characteristics (weight, hydrodynamics, density), so we will repeat our evaluation methods as we iterate. Integrating concepts like Degrade to Function [19] will also allow us to embrace the eventual degradation of our system in the ocean.

While water can be seen as a design challenge, it can conversely be an opportunity. Our prototype sensors rely on water's temperature-based expansion and high thermal mass.Future work could turn further water properties into opportunities, such as viscosity, cohesion, adhesion, and index of refraction—these suggest new types of sensors, timers, actuators, and other computational structures. We also want to explore harnessing ocean energy to power the system: System 2 uses thermal energy as power, while System 1 could use ocean currents. The accumulation of algae could also be encouraged



(a) (b)

Figure 7: Setup for evaluating loss of water flow. (a) Power source used directly resulting in the water wheel turning under water. (b) Water flow goes through the pinch valve controller, and the wheel does not turn under water.

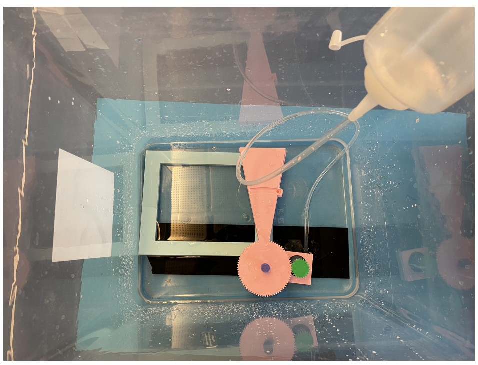


Figure 8: Setup for evaluating System 1 end-to-end

Figure 9: Setup for evaluating System 2 end-to-end and testing temperature sensitivity

(design-wise or through specific material use) in places where it would enhance structural integrity rather than hinder interaction.

5.2 Enhancing and Expanding ReefSense

5.2.1 Enhanced computation. We plan to unite our two system designs: the water flow from System 1 would allow for logical operation using water-tuned versions of AirLogic widgets [26], e.g. to only shade the reef if both temperature AND light levels are too high. In future research, we will tune AirLogic to work with water instead of air. This will also require integrating new sensors, such as bio-inspired photo actuators [4].

We further envision expanding ReefSense to be able to structurally store information in off-line memory devices [27], enabling long-term temperature and wave modeling. Unlike today, when surface water temperature is used as a proxy for temperature at the depth of the corals [20], systems like ReefSense could measure and respond to actual conditions. In terms of waves, many artificial reefs are currently deployed to break waves before they hit the coast [15]: by leveraging the fact that water becomes denser as it becomes deeper, we could create devices that track the depth of waves passing over the reef.

5.2.2 Design tools. A reef's needs for size, shape, degree of shading, and other specific environmental factors all depend on its specific characteristics. This calls for a ReefSense design toolkit that can help designers simulate and create customized ReefSense deployments for specific artificial reefs. Here we are hopeful for collaborations with biologists or ecologists [17] that can help us consider unforeseen issues [23].

6 Conclusion

We demonstrated ReefSense, a system of prototypes integrating (fluidic) sensing and actuation into artificial reefs. Our prototypes demonstrate a method to shade artificial reefs from sunlight that put corals at risk of bleaching under high sea temperatures. We described how two different ReefSense systems are achieved through prototypes, measured the performance of both system and discuss further work needed to achieve computing artificial reefs. We believe our work can contribute to the creation of sustainable, electronics-free interactive objects that can aid humans in responding to the climate crisis through mitigating coral bleaching.

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