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A Sensor-Actuated Surface Vehicle for Floating Plastic Waste Retrieval

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Abstract

This paper reports the construction of a small sensor-actuated surface vehicle intended for the retrieval of floating plastic debris, and provides the quantitative framework against which such a machine must eventually be judged. The prototype couples an ultrasonic ranging sensor to an ATmega328-based Arduino controller which, on detection, commands servo motors that position a net-type capture mechanism and a relay-switched DC motor that provides propulsion and drives a downstream size-reduction stage. The build was completed and its actuation sequence demonstrated. What the campaign did not produce is any measurement: no capture rate, no detection range or detection reliability, no sweep speed, no propulsion power and no endurance figure was logged, and consequently not one performance number is reported here, nor is one estimated. Two structural limitations are additionally identified from first principles rather than from testing. An air-coupled ultrasonic ranger returns time of flight to the nearest reflecting surface and carries no material information whatever, so the sensing stage detects an object, not plastic, and cannot discriminate debris from foam, weed, wave crest or hull wake. And the same ranger's calibration drifts with air temperature, giving a range error at 30 degrees Celsius of about minus 2 % against a fixed-speed assumption. This revision additionally closes the throughput relation with published areal densities rather than assumed ones: at the 10 to 100 kg per square kilometre that characterise a major accumulation zone, a sub-metre capture width sweeping at 1 m/s with perfect capture recovers of the order of 0.14 to 1.44 kg in an eight-hour sortie. That figure is derived, not measured, and it establishes that the environment, not the mechanism, sets the ceiling on this class of machine. The paper consolidates the ranging, throughput, hull-resistance and endurance relations that determine whether such a vehicle is viable, separates built-and-demonstrated capability from unmeasured and unimplemented capability, and specifies the exact trials required to convert the prototype into a quantitative result.

Nomenclature

Symbol	Meaning
d, c, t_{tof}	Range to the nearest reflecting surface (m), speed of sound in air (m/s) and round-trip echo time (s)
T_{air}	Air temperature (degrees Celsius)
σ	Areal density of floating debris (kg/m^2)

w, v	Effective capture width of the mechanism (m) and sweep speed over the water (m/s)
η_c	Capture efficiency of the mechanism
m-dot	Capture rate (kg/s)
R_h, C_d	Hull resistance (N) and drag coefficient
ρ_w, A_w	Water density (kg/m^3) and wetted frontal area (m^2)
P_{prop}, P_{aux}	Propulsion power and auxiliary hotel load (W)
E_{bat}, t_{end}	Usable battery energy (Wh) and endurance (h)
T_{sortie}, m_{sortie}	Duration of one sortie (s) and mass recovered in it (kg)

Introduction

Floating plastic debris in the marine environment is now a well-characterised environmental problem, and the mass balance between input, accumulation and removal is the subject of a substantial quantitative literature [1], [2]. That literature has one consistent implication for engineering: because inputs are measured in millions of tonnes per year, any proposed removal technology is meaningful only if its throughput is stated in mass per unit time and its energy cost in energy per unit mass recovered. A cleanup machine whose collection rate is unknown cannot be compared to any alternative, cannot be scaled, and cannot be costed.

This paper reports a small surface-vehicle prototype built to demonstrate the sense, decide and actuate loop of debris retrieval: an ultrasonic sensor detects an obstruction ahead, an Arduino controller interprets the range, servo motors position a net-type capture mechanism, and a DC motor provides propulsion and drives a size-reduction stage. The build works as a demonstration of mechanism. The paper's purpose is to state precisely what that demonstration does and does not establish, and to supply the relations against which the next iteration must be measured.

1. Problem Statement

Prototype cleanup vehicles are reported frequently, and almost all report the same thing: that the mechanism actuates. Very few report throughput, capture efficiency or specific energy, which are the only quantities that determine whether a design is worth scaling. At the same time, oceanographic studies of debris distribution supply the areal densities such a machine would encounter, but assume idealised collection. There is little work that connects a transparently reported bench prototype to the throughput and energy relations that govern its usefulness, while being explicit that the prototype's own performance was never measured.

2. Objectives

The specific objectives of the work are as follows:

- To build a surface vehicle that demonstrates the detect, position, capture and reduce sequence for floating debris.
- To report what the prototype was observed to do, and to state explicitly that no performance quantity was logged.
- To identify from first principles, rather than from testing, the structural limitations of an air-coupled ultrasonic sensing stage.
- To consolidate the ranging, throughput, resistance and endurance relations that govern this class of vehicle.
- To close the throughput relation with published areal densities, so that the achievable capture rate is bounded by real numbers rather than by assumed ones.
- To specify the trials that would convert the prototype into a quantitative result.

3. Scope and Delimitation

The study covers the construction of the vehicle, the relations governing ranging, capture throughput, hull resistance and endurance, and the specification of the instrumentation that was absent. It excludes any claim of capture rate, capture efficiency, detection range, detection probability, sweep speed, propulsion power, endurance or recovered mass for this build, because none was measured. It also excludes the camera, data-analysis and on-site recycling stages named in the source design documentation, which were not constructed. The vehicle was exercised on the bench only; no open-water trial was conducted, and no claim about seakeeping or wet-surface acoustic performance is made.

4. Contributions

1. A transparent report of what the prototype was observed to do, and an explicit statement that no performance quantity was logged.
2. A first-principles identification of two structural limitations of the sensing

stage, namely material blindness and thermal drift, derived from the ranging relation rather than from testing.
3. A consolidated set of governing relations for ranging, capture throughput, hull resistance and endurance.
4. A quantified throughput ceiling, new to this revision, obtained by substituting published areal densities for the assumed values used previously, which shows that the environment rather than the mechanism bounds this class of machine.
5. A separation of built-and-demonstrated, built-but-unmeasured and unimplemented capability, with the trial plan that would close the gap.

The remainder of the paper is organised as follows. Section II reviews related work and fixes the reference densities. Section III develops the governing relations. Section IV describes the prototype and the method. Section V reports and interprets the campaign. Section VI discusses the findings, Section VII states the limitations, and Section VIII gives the proposed instrumented architecture and trial plan. Sections IX and X give the conclusion and the future scope.

Related Work

Jambeck and colleagues [1] quantified land-based plastic input to the ocean and established the scale against which any removal rate must be compared. Eriksen and colleagues [2] estimated the mass and particle count of floating debris and, importantly for Section III, reported the areal densities that determine achievable capture rate: it is the sparseness of debris, not the capability of the net, that usually bounds throughput. Lebreton and colleagues [7] mapped one major accumulation zone in detail and supply the density figures used in Section V-E.

On the sensing stage, the standard treatment of air-coupled ultrasonic ranging [3] establishes both relations used here, the time-of-flight range and the temperature dependence of the speed of sound, and makes clear that such a sensor is a range finder and not a material classifier. Where material discrimination is required, the reported approaches are optical or spectroscopic [4], not acoustic, which is directly relevant to the limitation identified in Section V-C. For the vehicle stage, standard naval-architecture treatments of resistance and propulsion [5] give the cube-law power relation used in Eq. (4), and the Arduino platform [6] supplies the control layer.

Table 1. Representative Related Work and its Relation to This Study

Ref.	Year	Focus and scope	Method and validation	Relation to this work
[1]	2015	Plastic input to the ocean	Mass-balance study of waste streams	Sets the scale any removal rate must meet
[2]	2014	Floating debris mass and count	Field sampling; global model	Source of areal density σ in Eq. (3)
[3]	—	Air-coupled ultrasonic ranging	Standard sensing treatment	Basis of Eqs. (1), (2)
[4]	2018	Polymer identification by spectroscopy	Laboratory classification	Shows what acoustic sensing cannot do
[5]	—	Ship resistance and propulsion	Standard naval architecture	Basis of Eq. (4)
[6]	—	Arduino and ATmega328 platform	Vendor documentation	Control and actuation layer
[7]	2018	Mapping of a major accumulation zone	Vessel and aerial survey with calibrated model	Source of the density figures used in Section V-E

Because the analysis of Section V-E depends on the areal density a vehicle would actually encounter, it is necessary to fix that quantity from published survey work rather than to assume it. Table 2 collects the relevant figures.

Table 2. Published Reference Values for Floating-Debris Density and Acoustic Ranging

Item	Published value	Source
Definition of the accumulation zone boundary	The zone is delimited at 10 kg of plastic per square kilometre	Survey and model [7]
Area of that zone	1.6 million square kilometres	Survey and model [7]

Mass afloat within it	About 79,000 tonnes, with a range of 45,000 to 129,000	Survey and model [7]
Density within the zone	Of the order of 100 kg per square kilometre in the core, falling to 10 at the outer limit	Survey and model [7]
Size distribution by mass	More than three quarters of the mass is carried by debris larger than 5 cm; at least 46 % is fishing net	Survey and model [7]
Size distribution by count	Microplastics are 8 % of the mass but about 94 % of the estimated 1.8 trillion pieces	Survey and model [7]
Speed of sound in air at 20 degrees Celsius	About 343 m/s	Physical constant [3]

Values are published survey results and physical constants. They are used in Section V-E to bound the capture rate of a machine of this class. None is a measurement of the prototype described in Section IV.

Governing Relations

1. Ranging

An ultrasonic ranger measures the round-trip time of an emitted pulse and infers range as

$$d = \frac{c\,t_{tof}}{2} \qquad (1)$$

where the speed of sound in air varies with temperature approximately as

$$c \approx 331.4 + 0.6\,T_{air} \quad [\text{m/s}] \qquad (2)$$

Firmware that assumes a fixed value of c, as the common implementations do, therefore carries a systematic range error whenever the air is not at the assumed temperature. That fractional error is

$$\frac{\Delta d}{d} = \frac{c_{assumed}}{c(T_{air})} - 1 \qquad (8)$$

Fig. 1 plots it for a nominal 343 m/s assumption. At a tropical surface-air temperature of about 30 degrees Celsius the true speed of sound is 349.4 m/s, so the indicated range is short by 1.8 %. Over the range 0 to 40 degrees Celsius the error swings from about plus 3.5 % to about minus 3.5 %, which for a threshold-triggered capture sequence is the difference between actuating early and actuating late.

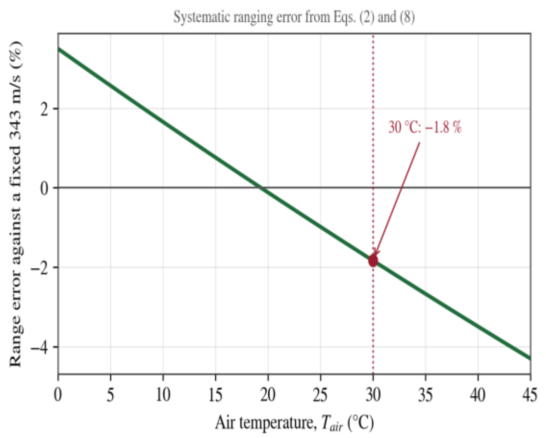

Figure 1: Systematic ranging error introduced by assuming a fixed speed of sound, from Eqs. (2) and (8). The prototype firmware uses a fixed value.

2. Capture Throughput

For debris of areal density σ swept by a mechanism of effective width w moving at speed v with capture efficiency η_c, the mass capture rate is

$$\dot{m} = \sigma w v \eta_c \qquad (3)$$

Equation (3) is the central design relation, and it exposes the economics immediately: throughput is linear in speed and width, but is bounded above by the environment through σ. Integrated over a sortie of duration T_{sortie}, the recovered mass is

$$m_{sortie} = \sigma w v \eta_c T_{sortie} \qquad (7)$$

Equation (7) is the form in which the relation is evaluated in Section V-E, because a mass per sortie is the quantity an operator can act on.

3. Resistance, Power and Endurance

Hull resistance rises with the square of speed and propulsion power with its cube [5],

$$R_h = \tfrac{1}{2}\rho_w C_d A_w v^2 ,$$
$$P_{prop} = R_h v = \tfrac{1}{2}\rho_w C_d A_w v^3 \qquad (4)$$

Endurance on a battery of usable energy E_{bat} is then

$$t_{end} = \frac{E_{bat}}{P_{prop} + P_{aux}} \qquad (5)$$

and the mass recovered per unit energy, which is the figure of merit that determines whether the vehicle is worth deploying, follows as

$$\frac{m}{E} = \frac{\dot{m}\,t_{end}}{E_{bat}} = \frac{\sigma w \eta_c v}{P_{prop} + P_{aux}} \qquad (6)$$

Because power grows as the cube of speed while capture grows linearly, the figure of merit falls as the inverse square of speed once propulsion dominates the hotel load: sweeping faster collects more debris per hour but less debris per joule. An optimum therefore exists at the speed where propulsion power becomes comparable with the auxiliary load. Fig. 2 shows both sides of the trade-off. Its position cannot be located for the present vehicle, since neither side of it was measured.

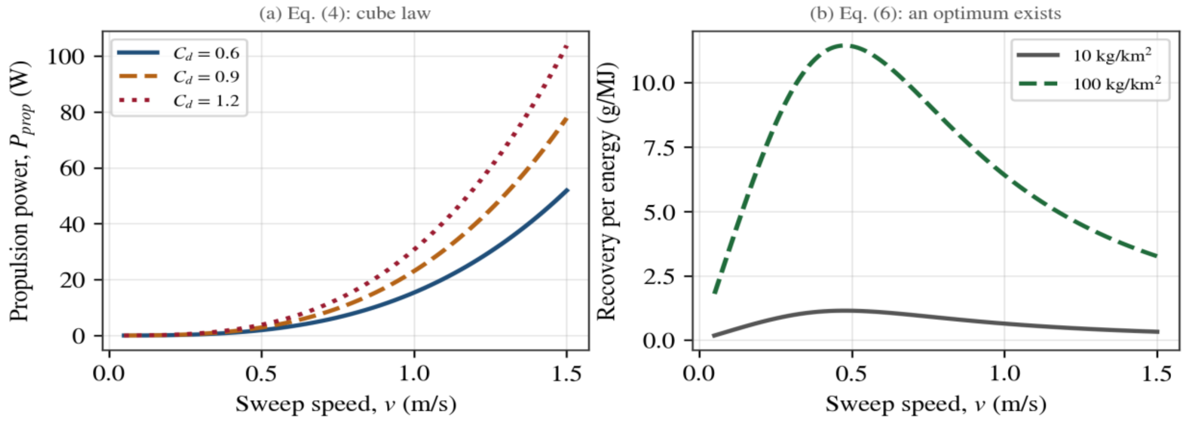

Figure 2: (a) Propulsion power from Eq. (4) for three drag coefficients; (b) recovery per unit energy from Eq. (6), showing the optimum that the cube law creates. Hull parameters are illustrative, since the hull was not characterised.

Prototype and Methodology

1. Architecture

Fig. 3 shows the prototype. An ultrasonic ranger scans ahead of the vehicle. Its echo time is converted to range by the Arduino controller, which on detection commands servo motors to position the net-type capture mechanism and switches the DC motor through a relay for propulsion and for the downstream size-reduction stage. A regulated supply derived from the battery feeds the logic. The three items shown as absent at the foot of the figure are the ones that would be required to evaluate any relation in Section III.

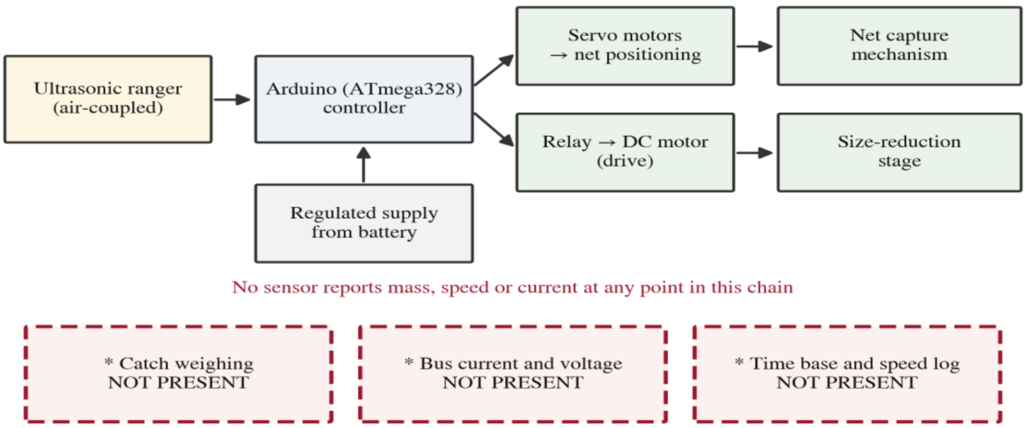

Figure 3: Prototype architecture: detect, position, capture, reduce. No sensor reports mass, speed or current at any point in this chain.

2. Apparatus

Table 3 lists the apparatus as documented; blanks indicate ratings the source material does not state.

Table 3. Apparatus Used in the Prototype

Item	Type / rating	Quantity
Controller board	Arduino (ATmega328)	1
Ultrasonic ranger	Air-coupled, echo-timing	1 or more
Servo motor	Positional	2
DC motor	Rating not stated in the record	1
Relay module	Rating not stated in the record	1
Regulated power supply	Rating not stated in the record	1
Net capture mechanism	Fabricated	1
Size-reduction stage	Motor driven	1
Connecting wires	—	as required

The effective capture width, the hull dimensions, the battery capacity and the motor ratings are not recorded. Their absence is why the relations of Section III cannot be evaluated for this build even in principle, independently of the missing instrumentation.

3. Procedure

1. Assemble the chain from ranger through controller to servo and relay, and on to the capture and drive stages, powered from the regulated supply.
2. Flash the controller from the Arduino IDE with the ranging and actuation routine.
3. Present a target within the ranger's field and confirm that the capture sequence actuates.

Results

1. What Was Observed

The complete chain was assembled and the actuation sequence was demonstrated: presenting a target caused the controller to command the servo and relay outputs, and the capture and drive stages responded. That is the whole of the observed result, and it is reported without extension.

2. What Was Not Measured

No quantity in Section III was logged. There is no recorded capture rate, no capture efficiency, no detection range or detection probability, no sweep speed, no motor current, no propulsion power, no endurance, and no mass of material recovered. Consequently none of Eqs. (3) to (7) can be evaluated for this vehicle, and no performance figure is reported. Table V states this explicitly, quantity by quantity, in preference to a general disclaimer.

3. The Sensing Stage Is Material-Blind

This limitation follows from Eq. (1) and does not require a trial to establish. An air-coupled ultrasonic ranger reports the round-trip time to the nearest surface that reflects sufficient acoustic energy. It returns a distance; it does not return composition, colour, buoyancy or polymer type. A floating bottle, a clump of weed, a wave crest, a piece of driftwood and a bird on the water are, to this sensor, the same event. The system as built therefore performs obstacle detection, and the description of it as plastic detection is not supported.

The published size distribution sharpens the point. In the accumulation zone surveyed in [7], microplastics account for about 94 % of the pieces but only 8 % of the mass, while more than three quarters of the mass sits in debris larger than 5 cm, of which at least 46 % is derelict fishing net. A ranging sensor cannot distinguish a net from a wave, and a net is both the most valuable target by mass and the most hazardous object for a net-type capture mechanism to encounter. Where polymer discrimination is genuinely required, the reported techniques are optical or near-infrared spectroscopic [4]; adding such a stage, or accepting indiscriminate capture followed by sorting on shore, are the two honest design options.

A second consequence of Eq. (1) is that a wet transducer face, spray, and the acoustically soft and uneven water surface all degrade echo return in ways that a bench trial in still air will not reveal. The prototype was exercised on the bench only.

4. The Thermal Drift of the Ranging Stage

The second structural limitation is quantified in Section III-A and Fig. 1. It is worth separating from the first because it is straightforwardly correctable: a temperature sensor and one line of firmware substituting Eq. (2) into Eq. (1) remove it entirely. Table 4 records the computed error at three temperatures. These are computed values, not measurements of this ranger, whose actual accuracy was never checked against a reference.

Table 4. Computed Range Error Against a Fixed 343 m/s Assumption

Air temperature	True speed of sound	Range error, Eq. (8)	Error on a 2 m range
0 degrees C	331.4 m/s	plus 3.50 %	plus 70 mm
20 degrees C	343.4 m/s	minus 0.12 %	minus 2 mm
30 degrees C	349.4 m/s	minus 1.83 %	minus 37 mm
40 degrees C	355.4 m/s	minus 3.49 %	minus 70 mm

Computed from Eqs. (2) and (8) for a firmware constant of 343 m/s. The transducer's own accuracy, beam width and minimum range were not characterised, so these figures bound one error term only and are not a calibration of this sensor.

5. Closing the Throughput Relation with Published Densities

The prototype's own performance is unknown, but Eq. (3) can now be evaluated with real numbers rather than assumed ones, and doing so is far more useful than an invented capture rate. Taking the density figures of Table 2, an effective capture width of 0.5 m appropriate to a vehicle of this size, a sweep speed of 1 m/s and a capture efficiency of unity, which is generous, Eq. (7) gives the results in Table 5. Fig. 4 shows the capture rate against speed and Fig. 5 the mass per sortie against capture width.

Table 5. Recovered Mass Computed from Eq. (7) at Published Areal Densities

Areal density σ	Capture rate	Per 8 h sortie	Area swept per sortie	Assumption set
10 kg/km^2 (zone outer limit)	18 g/h	0.144 kg	0.0144 km^2	w = 0.5 m, v = 1 m/s, η_c = 1
100 kg/km^2 (zone core)	180 g/h	1.44 kg	0.0144 km^2	w = 0.5 m, v = 1 m/s, η_c = 1
1000 kg/km^2 (hypothetical hotspot)	1.8 kg/h	14.4 kg	0.0144 km^2	w = 0.5 m, v = 1 m/s, η_c = 1

Computed from Eq. (7) using the published densities of Table II. The capture width, sweep speed and capture efficiency are stated assumptions, not measurements of this prototype, and perfect capture is assumed throughout, so these are optimistic bounds. The 1000 kg/km^2 row is hypothetical and is included only to show the scaling.

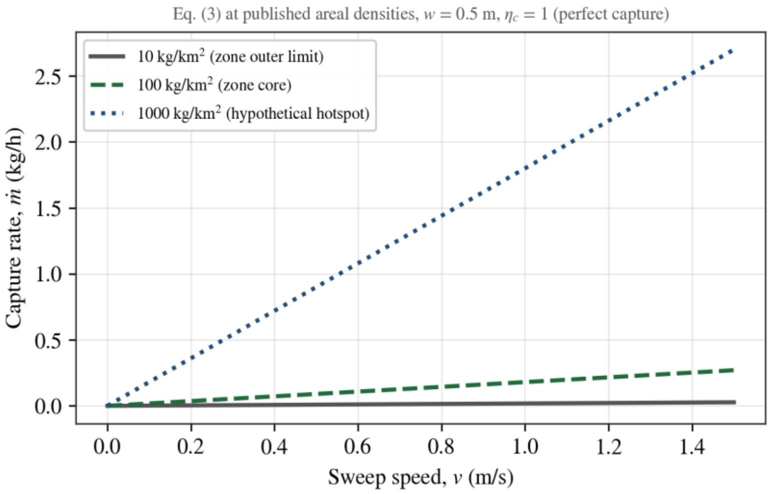

Figure 4: Capture rate from Eq. (3) at published areal densities, for a 0.5 m capture width and perfect capture efficiency.

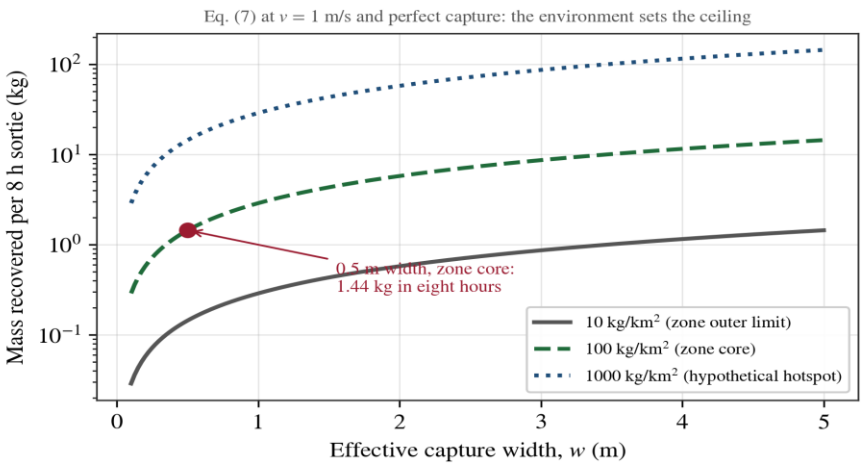

Figure 5: Mass recovered in an eight-hour sortie from Eq. (7), against effective capture width. The vertical scale is logarithmic.

Two consequences follow, and neither depends on any property of this prototype. First, a sub-metre vehicle working the core of a major accumulation zone under ideal conditions recovers of the order of a kilogram per working day. Widening the capture mechanism to 5 m, a tenfold increase, raises that only to about 14 kg. The environment, not the mechanism, is the binding constraint, exactly as Eq. (3) predicts. Second, and following directly, deployment siting dominates mechanism refinement: densities at river mouths, harbours and beach-front accumulations can exceed open-ocean values by orders of magnitude, and moving the same

vehicle to such a site changes the recovered mass by the same factor that a complete redesign of the net would not.
A scaling check makes the point concrete. The zone surveyed in [7] holds about 79,000 tonnes. At the 180 g/h obtained above for the zone core, and ignoring the fact that the density falls as material is removed, a single vehicle of this class would require of the order of 4.4 hundred million operating hours, or about 50,000 vehicle-years of continuous operation, to clear it. This arithmetic is not a criticism of the prototype, which was never intended for open-ocean work. It is the reason that throughput, and not actuation, is the quantity by which such machines must be reported.

6. What the Campaign Supports

Table 6 states the position quantity by quantity. Every row that records an absence is a row that a single afternoon of instrumented trials would convert into a result.

Table 6. Demonstrated, Unmeasured, Computed and Unimplemented Quantities

Quantity or capability	Value	Status
Detect and actuate sequence	functions	demonstrated
Servo positioning	functions	demonstrated
Drive and reduction stage	functions	demonstrated
Range error at 30 degrees Celsius	about minus 1.8 %	computed, Eq. (8)
Recovered mass per 8 h sortie in the zone core	about 1.44 kg	computed, Eq. (7), stated assumptions

Discussion

The prototype establishes that the detect, position, capture and reduce sequence can be implemented with commodity parts and a single microcontroller. That is a real result at the level of mechanism. What it does not establish is any quantity in Section III, and the paper keeps the two apart.

1. Scope Note on the Source Design

The design documentation refers to cameras and sensors monitoring the collection process, data analysis for reporting and decision-making, and on-site transformation of collected plastic for recycling or energy recovery. The constructed hardware contains no camera, no data-logging path and no analysis stage; the reduction stage is a motor-driven mechanism with no characterised output. These items are recorded as design intent and excluded from every claim in this paper.

2. Where the Design Effort Should Go

Section V-E has a design consequence that is worth stating plainly, because it inverts the usual priority of such projects. Effort spent on the capture mechanism buys throughput linearly in width. Effort spent on choosing where the vehicle operates buys throughput linearly in σ, and σ varies across sites by orders of magnitude rather than by factors of two. A vehicle that recovers a kilogram a day in an open-ocean accumulation zone may recover far more at a river mouth or harbour entrance without any change to the hardware at all. The relation says this; the prototype cannot, since it has never been operated anywhere.

3. Qualitative Position

Table 7 sets out the structural properties that can be asserted, each with the relation or source that supports it.

Table 7. Qualitative Properties of the Prototype and the Proposed Architecture

Feature	Property	Basis
Ultrasonic sensing	Range only; no material information	Eq. (1)
Fixed-c firmware	Systematic range drift with temperature	Eqs. (2), (8)
Servo capture	Positional actuation demonstrated	This work
Capture width	Sets throughput linearly	Eq. (3)
Sweep speed	Raises rate linearly, power cubically	Eqs. (3), (4)
Deployment siting	Dominates achievable rate through σ	[2], [7], Eq. (7)
Catch weighing and bus sensing	Converts every relation above into a result	Eqs. (3) to (7)

Limitations

The following limitations bound every claim made in this paper.

- No performance quantity was measured at any point. Capture rate, efficiency, detection range and probability, sweep speed, propulsion power, endurance and recovered mass are indeterminate for this build, not merely uncertain.

- The effective capture width, hull dimensions, battery capacity and motor ratings are not documented, so the relations of Section III could not be evaluated for this vehicle even if the instrumentation existed.
- The vehicle was exercised on the bench in still air. Wet transducer faces, spray and the acoustically soft water surface were never encountered, and their effect on echo return is unknown.
- The computed range errors of Table IV bound one error term arising from the fixed speed-of-sound assumption. They are not a calibration of this transducer, whose accuracy, beam width and minimum range were not characterised.
- The throughput figures of Table V and Figs. 4 and 5 use published densities but assumed values of capture width, sweep speed and efficiency, with perfect capture throughout. They are optimistic bounds on a class of machine, not measurements of this one.
- The scaling arithmetic in Section V-E ignores the fall in local density as material is removed, transit and recovery time, weather downtime and the fraction of debris below the surface. It is an order-of-magnitude statement only.
- The camera, data-analysis and recycling stages described in the source design documentation were not built and are excluded from every claim.

Proposed Instrumented Architecture and Trial Plan

Fig. 6 shows the minimum instrumentation that converts the prototype into a measurable machine. Three additions are structural: a load-cell or catch-weighing stage to give recovered mass, current and voltage sensing on the propulsion bus to give energy, and a time base so that both become rates.

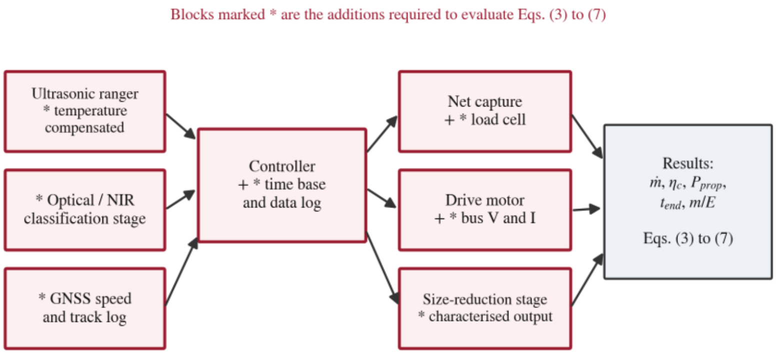

Figure 6: Proposed architecture. Blocks marked with an asterisk are the additions required to evaluate Eqs. (3) to (7).

1. Choosing the Sweep Speed

With bus power and catch mass both logged, Eq. (6) can be evaluated at several speeds and the vehicle operated at the speed that maximises recovery per joule for the observed debris density, rather than at whatever speed the motor happens to give. Fig. 2(b) shows that this optimum is real and not merely notional, since the cube law guarantees a maximum wherever an auxiliary load is present.

2. Handling Material Blindness

Two defensible options exist and should be chosen explicitly: add an optical or near-infrared classification stage ahead of capture [4], or accept indiscriminate capture and sort ashore. What is not defensible is to describe an acoustic ranger as a plastic detector.

3. Trial Plan

Table 8 sets out the trials that would convert the demonstration into a quantitative result, and Table 9 gives the context values that are explicitly assumptions or literature figures rather than results.

Table 8. Trial Plan Required to Make the Assessment Quantitative

Trial or measurement	Instrument or method	Quantity it yields
Catch weighing	Load cell on the capture stage, plus a time base	Capture rate, Eq. (3), as a real result

Bus instrumentation	Voltage and current sensing on the propulsion supply	P_{prop}, t_{end} and the figure of merit, Eqs. (4) to (6)
Ranger characterisation in situ	Detection probability against range for representative floating targets, over water, with spray	Detection range and reliability under real conditions
Temperature compensation	Air-temperature sensor and Eq. (2) substituted into Eq. (1)	Removes the error of Table IV entirely
Capture-width measurement	Direct measurement of the swept aperture	w, the remaining unknown in Eq. (3)
Capture-efficiency trial	Known mass of floating targets released across a measured sweep	η_c as a measured fraction
Timed open-water sortie	Sweep a known area of known debris density	Recovered mass, elapsed time and energy consumed
Material discrimination decision	Optical or near-infrared stage, or documented indiscriminate capture	Resolves the limitation of Section V-C

Table 9. Illustrative Figures (Assumptions and Literature, Not Results)

Item	Illustrative value	Status
Speed of sound in air at 20 degrees Celsius	343 m/s	physical constant [3]
Range error at 30 degrees Celsius	about minus 1.8 %	computed, Eq. (8)
Areal density σ	10 to 100 kg/km² in an accumulation zone	literature [7]
Capture width w used in Table V	0.5 m	assumption
Capture efficiency η_c used in Table V	1.0, that is perfect capture	assumption, deliberately optimistic

Only the range-error and recovered-mass entries are computed from stated relations. The density entry is taken from published survey work; the width and efficiency entries are assumptions used to draw the figures and are not measurements.

Conclusion

A small sensor-actuated surface vehicle for floating-debris retrieval was built, and its detect, position, capture and reduce sequence was demonstrated on the bench. No performance quantity was logged during the campaign: capture rate, capture efficiency, detection reliability, sweep speed, propulsion power and endurance are all absent from the record, and accordingly none is reported or estimated here.

Two structural limitations were established from first principles rather than from testing. An air-coupled ultrasonic ranger returns range and carries no material information, so the sensing stage detects objects rather than plastic; this matters especially because more than three quarters of the mass in a major accumulation zone sits in debris larger than 5 cm, of which nearly half is derelict fishing net, which a ranging sensor cannot distinguish from a wave. And a fixed speed-of-sound assumption in firmware produces a systematic range error of about minus 1.8 % at tropical surface-air temperatures, correctable with one temperature sensor.

The ranging, throughput, resistance and endurance relations governing such a vehicle were consolidated, and the throughput relation was closed with published areal densities rather than assumed ones. At the 10 to 100 kg per square kilometre that characterise a major accumulation zone, a 0.5 m capture width sweeping at 1 m/s with perfect capture recovers between about 0.14 and 1.44 kg in an eight-hour sortie, and widening the mechanism tenfold changes that only in proportion. The environment, not the mechanism, sets the ceiling, which places deployment siting ahead of mechanism refinement in determining usefulness. The figure of merit was further shown to fall as the inverse square of sweep speed once propulsion dominates, so an optimum operating speed exists and can be found once the bus is instrumented.

An instrumented architecture and a specific trial plan were given, requiring only a catch-weighing stage, bus current and voltage sensing, and a time base to convert this demonstration into a quantitative result.

Future Work

Several extensions follow directly from the limitations above.

- Weigh the catch-Add a catch-weighing or load-cell stage and a time base so that the capture rate in Eq. (3) becomes a real result.
- Instrument the bus-Add voltage and current sensing on the propulsion supply so that P_{prop}, t_{end} and the figure of merit of Eq. (6) can be evaluated, and the optimum sweep speed located.
- Characterise the ranger in situ-Measure detection probability against range for representative floating targets over water, with spray present, and add temperature compensation so that the error of Table IV is removed.
- Resolve material discrimination-Either add an optical classification stage or state explicitly that capture is indiscriminate and sorted ashore.
- Measure the capture width and efficiency-Determine w directly and obtain η_c from a released-target trial, so that the two remaining assumed terms in Eq. (7) become measured ones.
- Run a timed open-water trial-Sweep a known area of known debris density and report recovered mass, elapsed time and energy consumed, which is the minimum publishable result for a machine of this class.

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