

Design and development of a low-cost floater for sustainable fishing

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Design and development of a low-cost floater for sustainable fishing

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Abstract

While it is widely recognized that fish are an ecologically and commercially important group, our current knowledge of fish occurrence, composition (diversity), abundance and behavior (e.g. migration) is limited to anecdotal sightings and reports, often from laypersons. In situ marine monitoring bridges this gap and allows us to track and monitor marine life. One such system is the SOUND system: a swarm of low-cost Lagrangian floats that can non-invasively support aquaculture and fisheries, especially in remote areas and developing countries. The swarm of floats works together in a group and uses underwater acoustic communication. It provides long-term data on the fish population, which can shed light on the interdependencies of spatially segmented ecosystems, the top-down regulation of bio-geophysical processes and the sensitivity of the environment to anthropogenic stress factors. SOUND Floater consists of a piston-based buoy control system, an active sonar system with on-board analysis and a satellite communication module. It is capable of probing the water to a depth of 50 m while maintaining position with an accuracy of <10 cm, detecting schools of fish from a distance of 500 m and operating for 5 consecutive days. In this technical communication paper we present the detailed design of the SOUND prototype, including its mechanical, electrical and algorithmic parts. We report on results from laboratory pool and from two sea trials.

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Part of this work has been presented in the Oceans conference, Singapore, April, 2024. This journal version extended the conference publication by adding: 1) extended description of the electronics and acoustic components, 2) a revised design for the mechanical parts of the system, 3) results from two sea experiments, 4) explanation about the communication scheme of the floater. This work was sponsored in part by the Schmidt Marine Foundation via the Global Fisheries Tech Initiative, and by the European Union's Horizon Europe programme under the UWIN-LABUST project (project no. 101086340).

Index Terms

Lagrangian floater, marine monitoring, depth control, vehicle design, underwater acoustics, target tracking

I. INTRODUCTION

It is well known that fish are an important group both ecologically and commercially. Nevertheless, our knowledge of fish occurrence, composition, abundance and behavior is often limited to anecdotal sightings and reports, often obtained through invasive techniques such as net catches [1]. In this context, in situ marine monitoring, which allows remote monitoring of fish, can improve our knowledge of the presence and behavior of important fish populations. This includes increasing our knowledge of fish movements and abundance and understanding behaviors such as schooling, cohesiveness, and vessel avoidance. Monitoring fish populations will also enable efficient management of important commercial activities on the coast, in particular reducing bycatch by fisheries and promoting data-driven decision making in marine research [2]. Assessment of marine fauna must be based on efficient and preferably autonomous surveys to create large, labeled databases [3], and data must be correlated across time and space [4]. In developing countries, the main source of information on fish biomass comes from catch analysis due to a lack of government monitoring; therefore, an independent assessment is required. To this end, we have developed an autonomous system that performs on-the-fly monitoring of fish schools. This is the SOUND system.

The SOUND project designs a swarm of low-cost Lagrangian floats that drift with the water current and simultaneously perform active acoustic fish detection and on-site fish biomass assessment (Fig. 1). The result provides spatial information on the location, school size and biomass of the fish. The system provides long-term data on the fish population, which sheds light on the interdependencies of spatially segmented ecosystems, the top-down regulation of bio-geophysical processes as well as the environment and sensitivity to anthropogenic stressors. This will provide a comprehensive overview of the state of the food web in terms of biomass and reflect the current state of functioning of the marine ecosystem under study. Such an insight will provide a quantitative tool for reviewing management and planning efforts in relation to marine space. Especially in remote areas and in developing countries where advanced means of

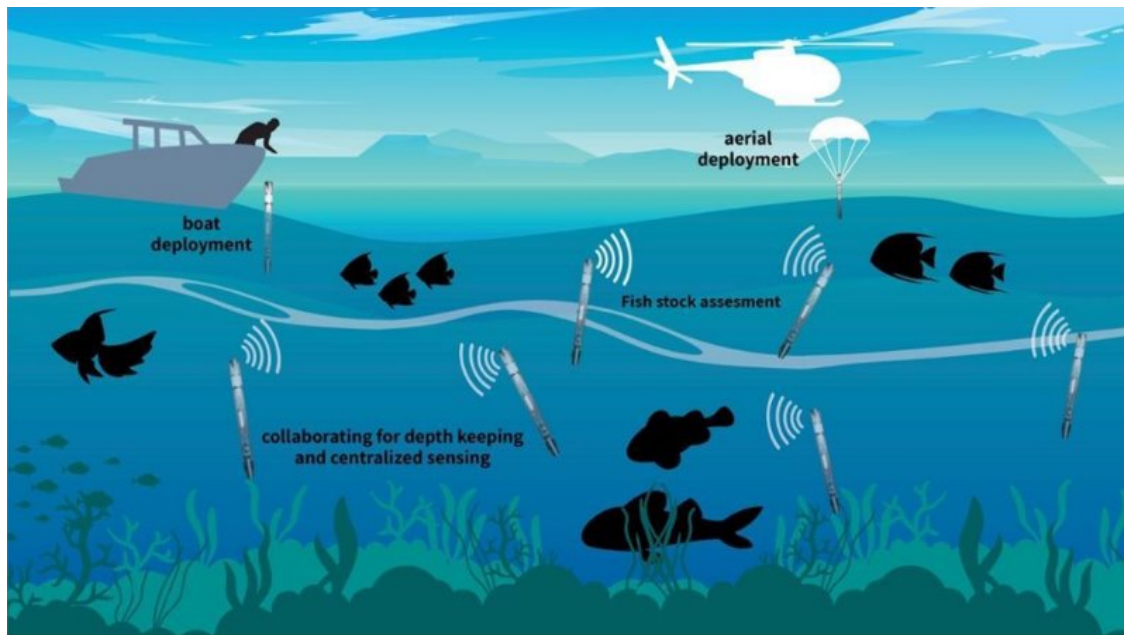


Fig. 1: Illustration of the SOUND system concept.

46 fish stock assessment are not available, a successful development that is plausible — because it
 47 is safe and does not require special permission — will greatly improve the efficiency and quality
 48 of geophysical surveys. SOUND’s capabilities will also benefit natural authorities by enabling
 49 them to properly guide and direct the local fishing industry. On a broader scale, SOUND can
 50 contribute to ecosystem monitoring by providing real-time tagged data on pelagic fish. Visual
 51 information can be found at [5].

52 SOUND floaters can profile the water column to a depth of 50 m or maintain the depth in
 53 cm resolution. Using an areal array, acoustic detection tracks individual fish up to a distance
 54 of 500 m and can relay information to other floaters up to a distance of 1 km. The system is
 55 designed to be energy efficient and can operate for up to 5 days. Information from multiple floats
 56 is exchanged via underwater acoustic communication and translated into the spatial distribution
 57 of fish; data that is currently only available from models. Once a joint decision has been made,
 58 the floaters can surface and transmit their results via satellite communication. The floaters are
 59 small and lightweight. They can be launched by a single person from a small ship. The self-
 60 construction of the mechanical, sensory and electrical parts enabled a low-cost development. This
 61 technical communication paper describes the technological contribution of the SOUND Floater:
 62 its underwater acoustic unit and the mechanism for controlling its buoyancy. The results of two

63 sea trials in the Red Sea and the Adriatic Sea are presented. Our aim is to support developers
64 of marine monitoring systems by sharing our design information.

65 The remaining of this paper contains an overview of similar fish monitoring solutions (Sec-
66 tion II), a description of the mechanical part of the SOUND floater (Section II-A), an introduction
67 to the electronic components of the floater (Section III) and details about the algorithms of the
68 floater (Section IV). The results of two field trials are given in Section V, and conclusions are
69 drawn in Section VI.

70 II. AVAILABLE SOLUTIONS FOR FISH MONITORING

71 Abundance indices for highly migratory animals are often based on fishery-dependent data,
72 which are known to be biased towards more sensitive species and certain types of habitat or
73 fishing gear [6]. In addition, fishery records are dependent on an incentive to report and are
74 therefore complicated by the typical omission of illegal, unreported and unregulated (IUU)
75 fishing, as well as discarded catches or catches from recreational [7]. To avoid this type of bias,
76 it is necessary to develop indiscriminate and reliable fishery-independent methods. An alternative
77 to this are dive surveys, in which fish species are visually recorded using a belt transect and the
78 species and individuals are recorded with a camera [8]. However, the area surveyed is limited -
79 both in terms of the area covered by the divers and the range of observation. Furthermore, for
80 safety reasons, dive surveys are only carried out in coastal areas and are virtually non-existent
81 in developing countries. As a result, acoustic systems are increasingly used for remote sensing
82 of marine fauna in ecological surveys [9].

83 Acoustic remote sensing techniques mostly involve narrow-beam sonar, which can image the
84 water column beneath a survey vessel (a research ship or often a torpedo-shaped Autonomous
85 Underwater Vehicle (AUV)), or a wide-beam sonar array deployed over fixed infrastructures
86 [10]. For example, multibeam echosounders mounted on Autonomous Surface Vehicles (ASV)
87 have been used to survey shipwrecks [11] and to map unique tufa structures [12]. Underwater
88 gliders, characterized by their low cost and long-term deployment potential, use a variety of
89 buoyancy control methods and different acoustic payloads and have proven to be well suited for
90 acoustic surveying [13], [14]. There are two main approaches for detecting targets using acoustic
91 emissions. The first is to transmit pulses with guard intervals inserted to suppress clutter. The
92 target is then found by tracking its possible path after a certain number of acoustic signals
93 have been emitted [15]. However, due to mismatches between the assumed clutter model and

94 the distribution of reflections from the detected targets, as well as hard assumptions about the
95 target's movement pattern, the current systems are prone to false detections, and robustness
96 for detecting different fish species is still a challenge. The second approach is continuous
97 active SONAR (CAS), which uses narrowband transmissions in multiple subcarriers to detect
98 Doppler components [16]. While the latter approach enables near real-time detection, its energy
99 consumption is too high for small, autonomous vehicles. In addition, the current approach to fish
100 biomass assessment relies on the rather imprecise relationship between acoustic target strength
101 and fish size [17], [18], [19], and no current approach reliably measures the biomass of detected
102 fish in-situ. Current approaches to assess marine biota are limited by the information provided.
103 In particular, current acoustic imaging techniques only detect objects directly beneath a survey
104 vessel and there are no reliable commercial methods for assessing fish biomass. Therefore, there
105 is a need to develop a reliable system for autonomous detection, classification and enumeration
106 of marine species [20]. This can not only improve the efficiency of environmental monitoring
107 tasks, but also pave the way for long-term and far-reaching investigations.

108 Flotation devices for monitoring the oceans are currently in use worldwide. The best-known
109 devices are the Argo floats [21], which are profiling floats that continuously scan the water
110 column while collecting temperature and salinity measurements. Depth profiling is carried out
111 by a hydraulic pump that inflates or deflates an external bladder. The depth-changing mechanism
112 of EM-APEX floats provides buoyancy control through a combination of an air pump that inflates
113 or deflates an air bladder while a piston simultaneously pushes or draws oil into a reservoir,
114 resulting in a change in average density [22], [23]. The mechanism used by the RAFOS floats
115 [24] controls their depth by adaptively adjusting a ballast weight to achieve buoyancy towards a
116 specific desired depth. Quasi-Lagrangian floats, which control their buoyancy by changing their
117 volume via the movement of two concentric cylinders on top of each other, are described in
118 [25]. However, the continuous acoustic monitoring is impaired by the strong noise emitted by
119 the motor during depth maintenance. Similar limitations exist when using a pump that forces oil
120 through a bladder to change the buoyancy [26], or a thruster for active depth control [27].

121 The floater described in [28] is designed to have negative buoyancy while thruster operation
122 is scheduled to ascend or descend. To reduce battery consumption and noise, the floater has a
123 parachute-like tarpaulin sheet that opens like an umbrella when the floater descends and closes
124 when it ascends. Another design is that of the aMussel robots [29] whose buoyancy control
125 mechanism consists of a piston and an impenetrable membrane which allows them to float on

126 the water surface or sink to the seabed. The SOUND floater builds on these designs by being
127 able to passively maintain depth by achieving neutral buoyancy, making it quieter and more
128 efficient operation.

129 *A. Mechanical design*

130 The main body of the SOUND floater consists of a 95 cm long Plexiglas tube, closed at
131 one end by the buoyancy mechanism and at the other end by a cap containing all the required
132 penetrators, switches, probes and active parts of the acoustic devices. The cap is designed to
133 separate into two parts that are relatively movable, as shown in Fig. 2. When the two parts
134 are joined together, the cap is closed and completely seals the top of the cylinder. When the
135 upper part of the cap is opened by a pull and-rotate motion, the user gains direct access to the
136 floater's electronics without having to open the entire system. This can be used for wired battery
137 charging, direct serial communication and general maintenance. Under the upper part of the cap
138 there is a groove for cable glands, sensors and probes so that these do not have to be placed on
139 the top of the device. Four hydrophones are mounted symmetrically on a bracket that radiates
140 outwards from the main body of the floater, while the acoustic projector is mounted on the top
141 of the cap. The mount for the hydrophones also serves as an attachment point for the 1 m long
142 antenna for the GPS and Iridium signal when the floater surfaces for data transmission (Fig. 3).

143 The depth control mechanism of the SOUND floaters is based on changing the buoyancy of
144 their elongated and bottom-heavy body. The design consists of a single chamber with variable
145 volume and a piston near the bottom of the main body so that the device becomes buoyant as
146 the volume changes. The floater has the greatest volume and buoyancy when the piston is fully
147 extended and the least volume and buoyancy when the piston is fully retracted. The actuator that
148 controls this change is a single piston with a linear drive mechanism and a rolling diaphragm
149 (Fig. 4). A lead screw is used for this linear mechanism as it can generate a large force and thus
150 overcome the high pressures at greater depths. A detailed view of the linear drive mechanism
151 can be found in Fig. 5. In it, a central spur gear is rotated by three other spur gears that are
152 connected to the motors. The nut connection couples the two outer nuts to the central spur gear.
153 The lower nut and the central spur gear are attached directly to the nut connection, while the
154 upper nut is connected via the shaft collar.

155 The use of several small electric motors coupled together makes it possible to drive the
156 buoyancy system in a float with low power consumption and low voltage, while still ensuring

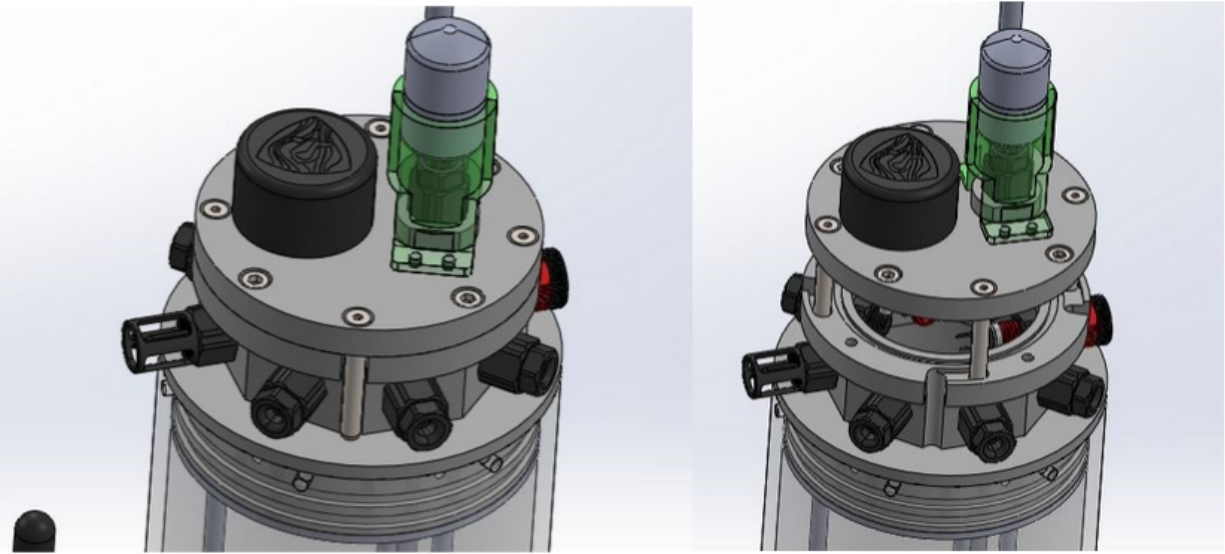


Fig. 2: SOUND floater prototype top cap design, sealed for deployment (left) and open for access (right).

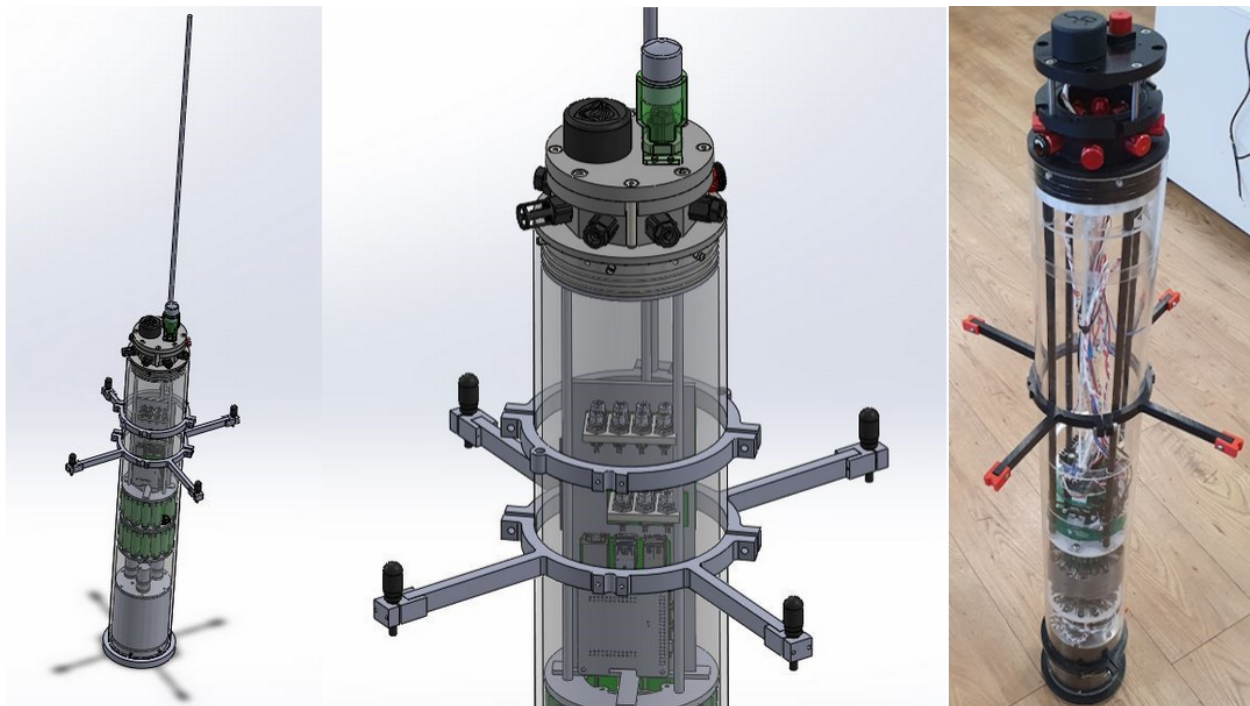


Fig. 3: SOUND floater prototype antenna and hydrophone mount design (left). Full hull prototype with hydrophone mount (right).

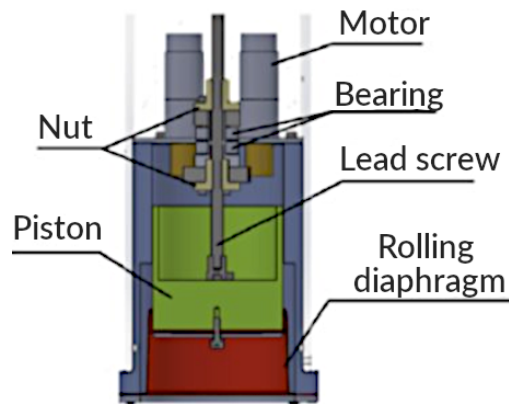


Fig. 4: SOUND floater buoyancy mechanism design cross-section.

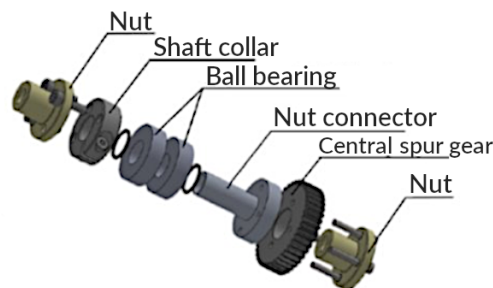


Fig. 5: Detailed view of the linear mechanism design.

157 high torque and fast actuation. This mechanical system is combined with two limit switches
 158 that detect the upper and bottom extreme positions of the piston when touched and activated by
 159 the lead screw. A Hall effect quadrature encoder and a pressure sensor enable low complexity
 160 control algorithms that allow implementation on low cost electronics. The functionality allows the
 161 floaters to maintain a specific depth, profile or surface for reporting or retrieving data. The motors
 162 themselves are made quiet by a vibration absorbing material (silicone) that is glued between the
 163 motor and the body of the floater. This decouples the motor from the floater enclosure to avoid
 164 disturbances to the acoustic unit. The reduction in motor usage during operation also serves to
 165 reduce noise and allows better energy efficiency.

166 Following several laboratory and field tests, the mechanism for controlling the buoyancy of
 167 the floater was redesigned to use a stepper motor and a modified gearbox. The use of a single
 168 stepper motor instead of coupled DC motors simplifies the control of the piston position as no
 169 external position sensor, such as an encoder, is required. The redesigned system contains only

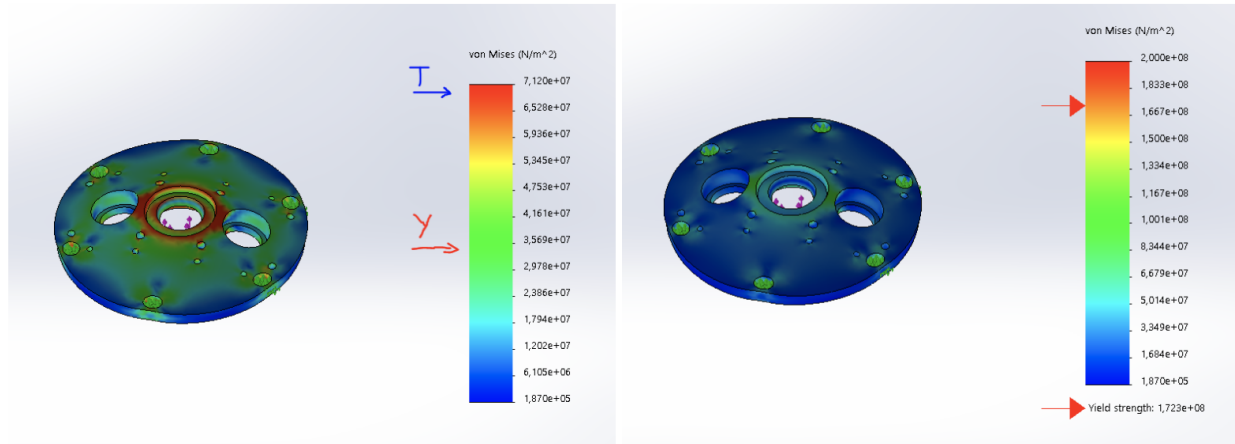


Fig. 6: Finite Element Analysis results of motor holding plate in initial floater design (left), new aluminium alloy version (right).

170 one limit switch in the center of the piston guide spindle area, which is used for the initial
 171 calibration of the piston position. The stepper motor used in the design has been selected so
 172 that it can deliver the required torque for surface machining from the maximum allowable depth
 173 while keeping current consumption low. The new design also includes a reinforced metal motor
 174 support plate structure to compensate for the weaknesses of the previous design (see FEA results
 175 in Fig. 6).

176 The floater reassembled with the new mechanism was tested in a laboratory pressure chamber
 177 for depths up to 6 bar to confirm that it is capable of delivering the desired and designed torque
 178 and piston speeds (nut torque 2.7 Nm and piston speed 83.65 mm/min).

179 III. ELECTRONICS DESIGN

180 The main electronics of the floater are divided into a depth control section and an acoustic
 181 detection section. Both have independent power supplies so that the noise-sensitive acoustic
 182 detection and processing part is isolated from the part dealing with the motor and buoyancy
 183 control. All electronics and battery support skeleton is connected to the top cap. The acous-
 184 tic sensing section consists of a Raspberry Pi 4 as the main board and includes the entire
 185 acoustic data acquisition and processing subsystem, while the general sensing, depth control
 186 and communication section uses an atmega32u4-based board (Arduino) to manage acoustic
 187 communication between each floater and between the floater and on-surface control via an

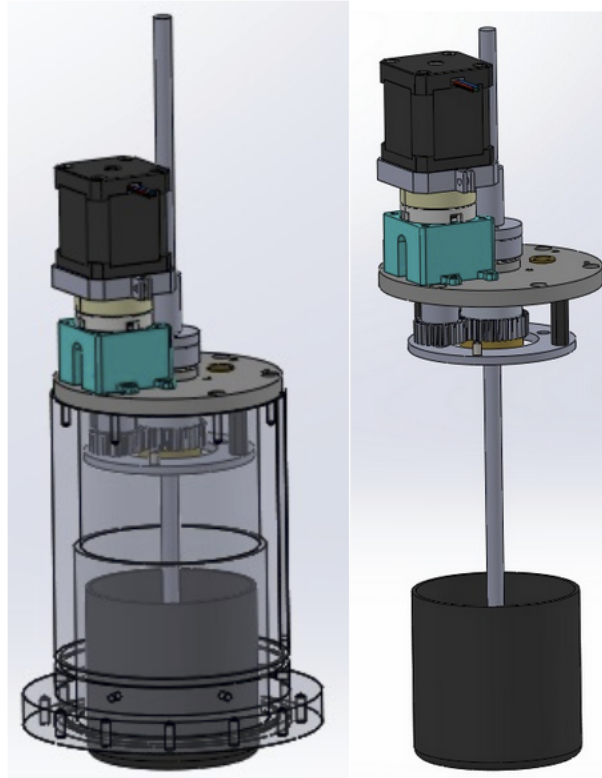


Fig. 7: The redesigned buoyancy mechanism, motors, and gearbox, for stepper motor.

188 acoustic modem (Nano-modem [30]). The Arduino-controlled part also collects data from the
189 pressure/temperature sensor on the top cap as well as the position encoder and limit switches
190 on the buoyancy mechanism, completing the loop for depth control. A block diagram of the
191 SOUND floater electronics is shown in Fig. 8.

192 A. Acoustic detection subsystem

193 The acoustic detection subsystem consists of a projector, four hydrophones, a preamplifier,
194 a sound card and a data processing card. Acoustic transmission is achieved by generating an
195 acoustic signal (a sequence of linear chirps) from the main processor, amplified by the power
196 amplifier and finally transmitted by the piezoelectric element in the frequency range of 30-41KHz.
197 The acoustic reverberations are sampled by 4 hydrophones. Each hydrophone is connected to
198 a preamplifier with 70 dB gain. A four-channel ADC samples the reflections synchronously at
199 96 ksp/s at 24 bit per sample. The analysis in the main processor detects targets and calculates

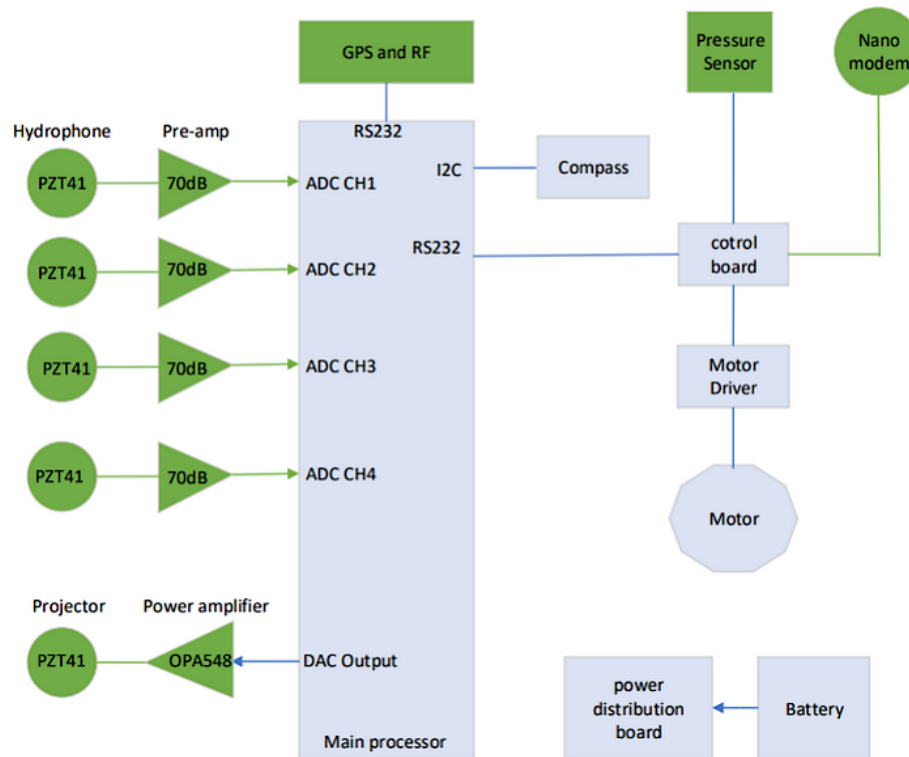


Fig. 8: Block diagram of the SOUND floater electronics.

200 their trajectories. The results are then transmitted to nearby floaters via the acoustic modem
 201 and/or to the user via an Iridium satellite module together with the GPS location of the floater.

202 1) Hydrophones:

203 The hydrophones were manufactured in-house and are based on the piezoelectric element PZT41
 204 with a size of OD33.7*ID29.9*13.3 mm and a capacitance of 7000pF±12.5%. A supporting
 205 network for each element adjusts the impedance of the hydrophone to a frequency of 34 kHz. To
 206 fabricate the hydrophone, two wires are soldered to the piezoelectric element with the positive
 207 pole of the signal connected to the inside of the element, as shown in Fig. 9. A waterproof
 208 polyurethane potting compound UR5041 is used for potting the hydrophone and the electronics.
 209 This resin system was selected due to its exceptional resistance to salt water. Using a template
 210 frame, care is taken to ensure that the piezoelectric element remains free during potting and
 211 does not come into contact with other components. To avoid bubbles in the potting compound,
 212 the element is then vacuumed for several minutes. The potting process is shown in Fig. 9, and
 213 a finished hydrophone unit can be seen in Fig. 10.

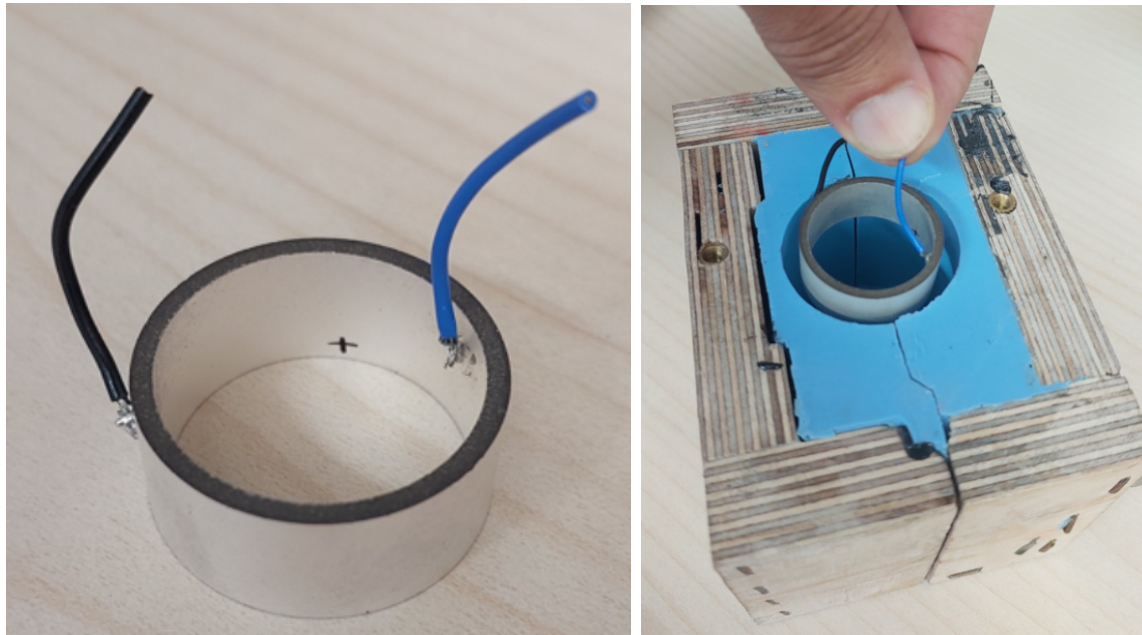


Fig. 9: Hydrophone production steps: preparing the piezoelectric element (left) and potting the hydrophone (right).

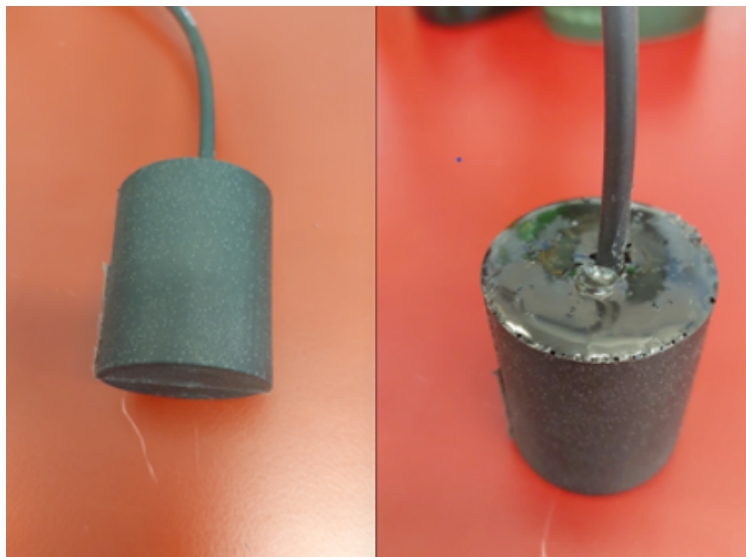


Fig. 10: Completed hydrophone for the SOUND floater.

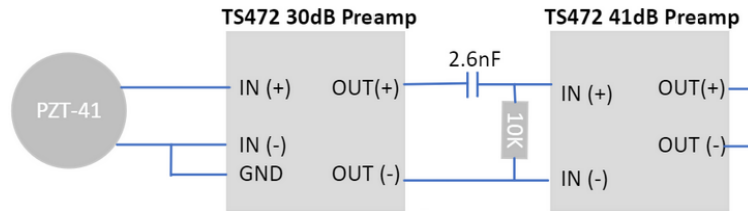


Fig. 11: Pre-amplifier connected to piezoelectric element.

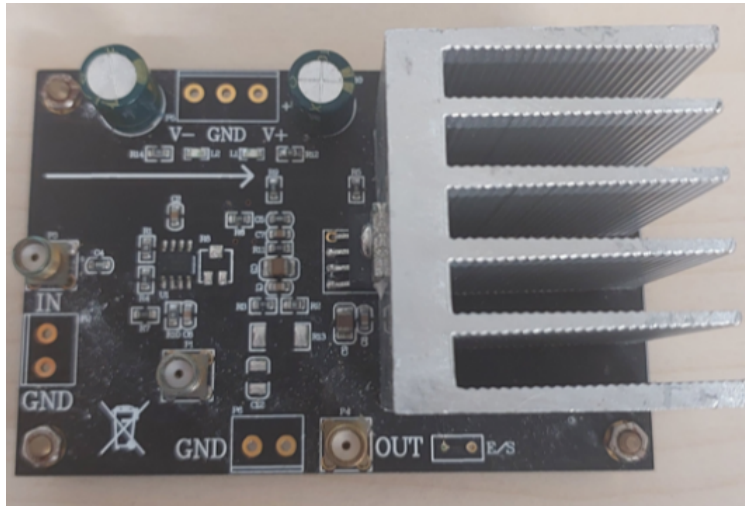


Fig. 12: SOUND floater acoustic subsystem amplifier.

214 2) Amplifiers:

215 The preamplifier consists of two TS472 boards, as shown in Fig. 11. It was designed for a low
 216 noise of $10nV/\sqrt{\text{Hz}}$ with an equivalent input noise at 1 kHz. It is a fully differential input/output
 217 circuit with a power consumption at 20 dB of 1.8 mA and a distortion of 0.1%. A high- pass
 218 filter at 5.9 KHz is integrated to avoid low-frequency noise and improve SNR.

219 The power amplifier used in the system is the OPA548 board shown in Fig. 12. The output
 220 impedance was adapted to the PZT41. The impedance matching circuit was calculated using
 221 the capacitance and resistance of the PZT41 at 30 KHz. The result is a 54 V peak-to-peak
 222 transmission when supplied with ± 28 VDC.

223 3) Data Acquisition:

224 The data acquisition (DAQ) component uses the OCTO sound card. This card comprises 6 input
 225 channels and 8 output channels, of which 4 inputs and 1 output are used. The channels can
 226 be sampled at up to 192 ksps at 24 bit. An isolated ADC and DAC help to reduce noise and

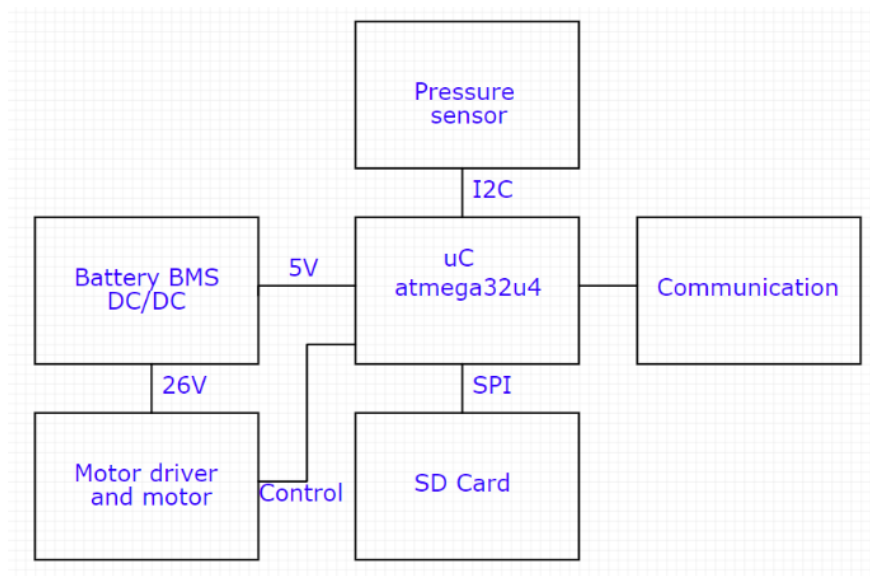


Fig. 13: Block diagram of the SOUND floater PCB internal communication protocols.

227 crosstalk. The sound card connects directly to the Raspberry Pi via a standard 40-pin header,
 228 with the GPIO lines broken out to control the preamp. The card has a full scale peak-to-peak
 229 output and input voltage of 4.8 V and 5.65 V, respectively, and a closed loop gain of -1.42 dB.

230 *B. Depth control subsystem*

231 The block diagram of the PCB communication of the depth control subsystem is shown in
 232 Fig. 13. The PCB itself with all the main components highlighted is shown in Fig. 14. The
 233 main board contains an interface for an acoustic modem with receive/transmit capabilities for
 234 communication, a microSD card for data logging and a real-time clock (RTC) module. For depth
 235 control, the floater contains an MS5837-30BA pressure/temperature sensor with a resolution of
 236 2 mm and an operating depth of up to 300 m. The TMC2208 stepper motor driver controls the
 237 17HS19-1684S-PG5 stepper motor with high precision and ensures that the piston moves by
 238 0.2 mm for each revolution of the motor.

239 The floater is operated with two battery packs. A battery management system (BMS) is
 240 responsible for balancing the cell load and managing the charging process. The cells used are
 241 Sony US18650VTC6 Li-ion battery cells. A single cell has 3000 mAh and a nominal voltage of
 242 3.7 V. For the depth control board, the battery configuration is a single power supply consisting
 243 of 2×7 cells connected in series with a nominal voltage of 25.9 V and a capacity of 6000 mAh,

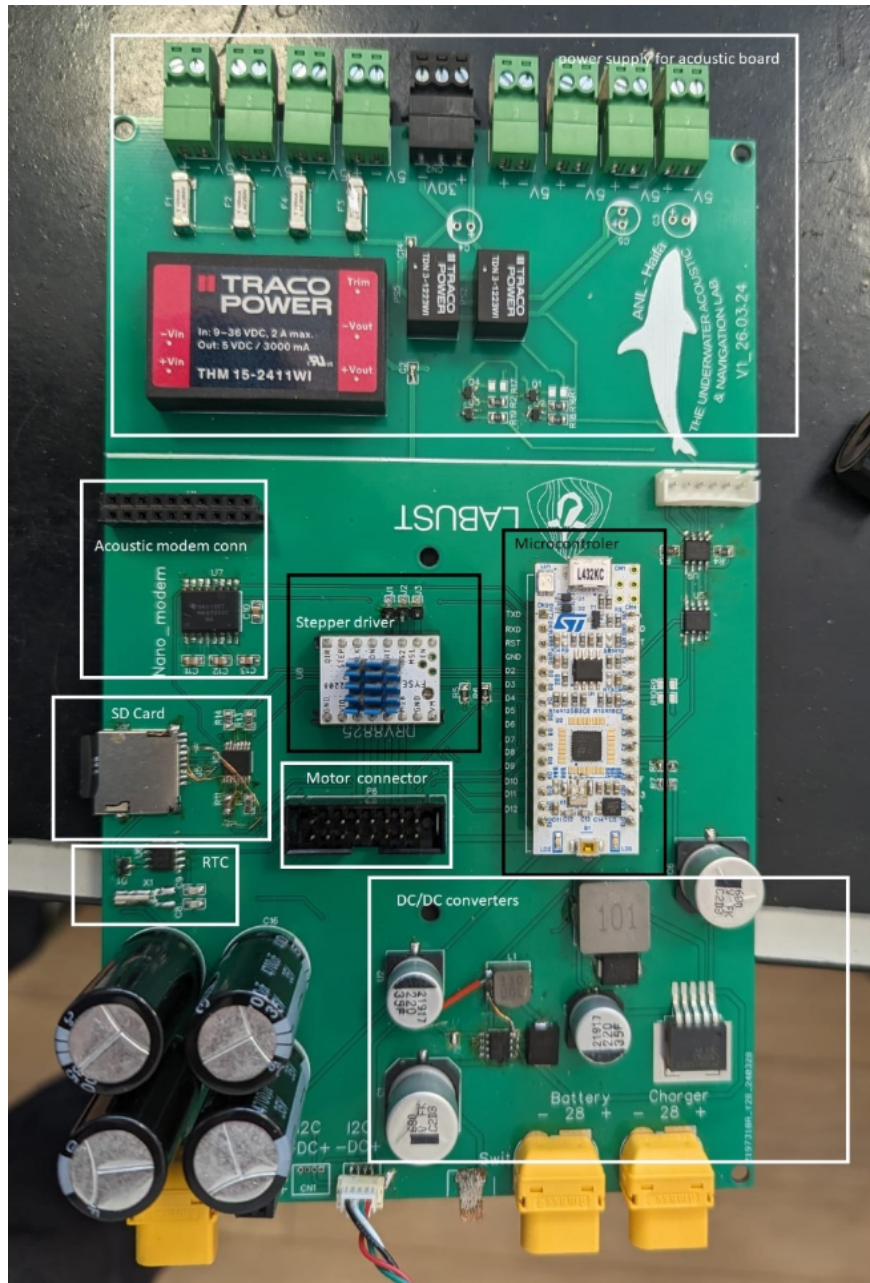


Fig. 14: SOUND floater main PCB.

244 giving 155 WH. For the acoustic subsystem, a dual power supply consisting of 1×14 cells
 245 connected in series for a nominal voltage of ± 25.9 V and a capacity of 3000 mAh is provided,
 246 resulting in 155 WhH. Finally, two rotary switches are installed to switch the acoustic and control
 247 boards on and off independently.

IV. SOFTWARE AND ALGORITHMIC DESIGN

248

249 The floater's main loop runs on the Arduino Micro, while the Raspberry Pi 4 goes through a
250 sleep/wake cycle to conserve power and wakes up when its advanced processing capabilities
251 are needed. The basic communication structure between the Raspberry Pi and the Arduino
252 subsystems within a single floater, as well as the exchange of information between different
253 floaters in the swarm, are illustrated in Fig. 15.

254 Controlled descent and ascent for vertical profiling is achieved by moving the piston from
255 a neutrally buoyant position defined by an encoder offset. To reduce motor activity, we target
256 the displacement of the piston to a minimum negative or minimum positive buoyancy, as the
257 speed of movement is not a priority. During operation, the floater is initially trimmed so that
258 the neutral buoyancy corresponds to a piston position where the piston bottom being flush with
259 the lower edge of the floater hull.

260 *A. Acoustic Detection*

261 The goal of the acoustic detection section of the SOUND floater is to detect multiple targets
262 up to 500 m away, track their trajectory, estimate their biomass and determine their bearing. For
263 this purpose, we have developed an active acoustic system with an omnidirectional projector
264 and a planery array of 4 hydrophones. The projector emits a sequence of linear broadband chirp
265 signals with a duration of 10 msc and a frequency band of 30 kHz-41 kHz. The chirp signals are
266 sent at 0.7 sec intervals to allow reverberation up to 500 m away before the next transmission
267 occurs. Each chirp signal is received synchronously by the 4 hydrophones and resampled after
268 baseband conversion in the Rasberi Pi 4 unit. Detection is performed for a sliding window of
269 20 such chirp emissions.

270 The development of the acoustic detection system involves a novel detection algorithm that
271 takes into account the temporal and spatial changes of the fish during detection. The algorithm
272 creates a 3D matrix from temporal-spatial observations. The temporal domain is the reverberation
273 received from the 20 emitted chirp signals. The spatial domain includes both distance and angle
274 estimates. The former is obtained by a normalized matched filter (cf. [31]) and measuring the
275 arrival time difference and multiplying it by the speed of sound speed, which is estimated from
276 depth and temperature measurements on board the floater and a sound speed model. The latter
277 is evaluated via beamforming performed for the 4 receiving channels. As the receiving array is
278 planar, only the horizontal angle (heading) is estimated. The information from the gyrocompass

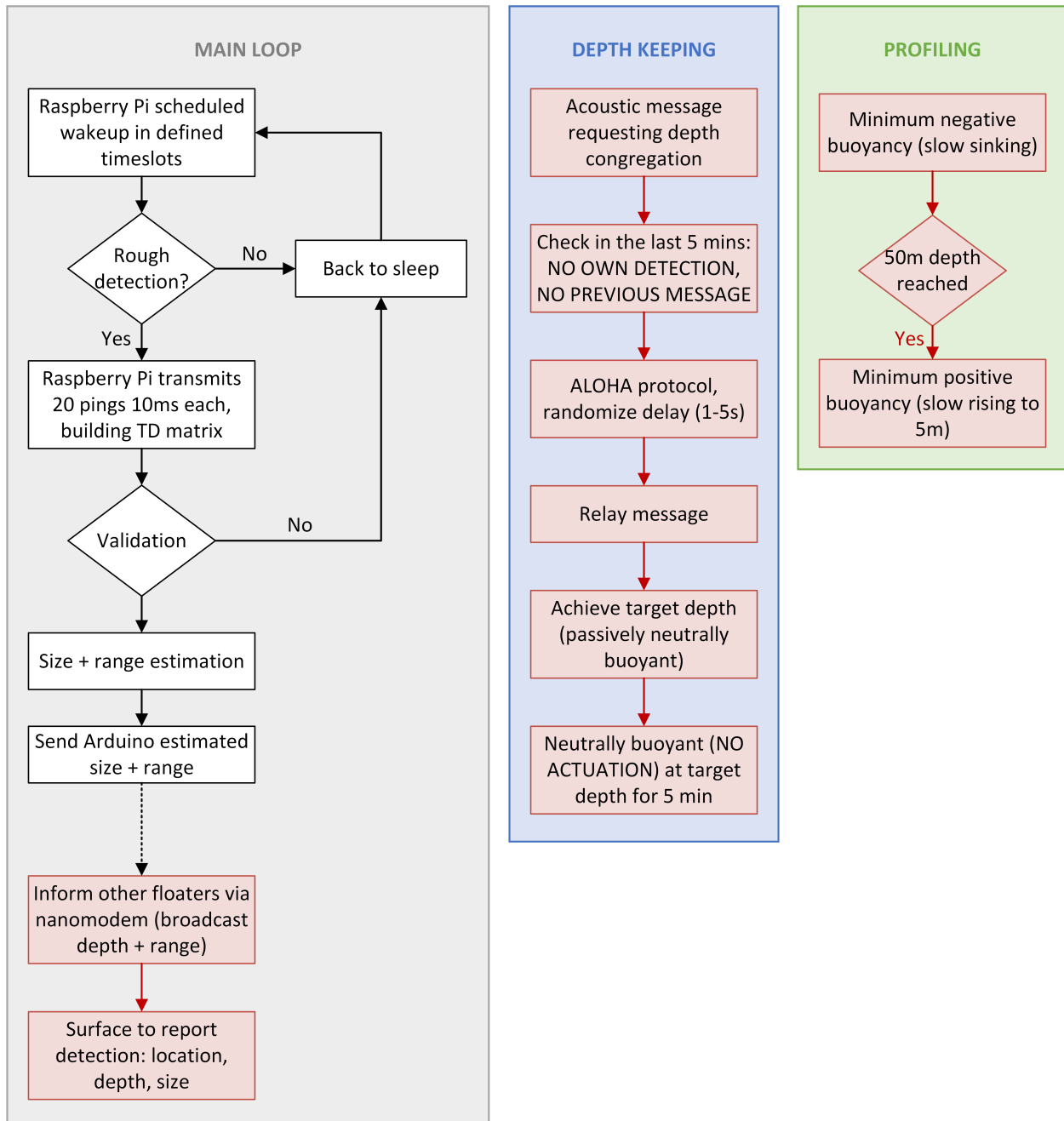


Fig. 15: Block diagram for the operation of the SOUND floater.

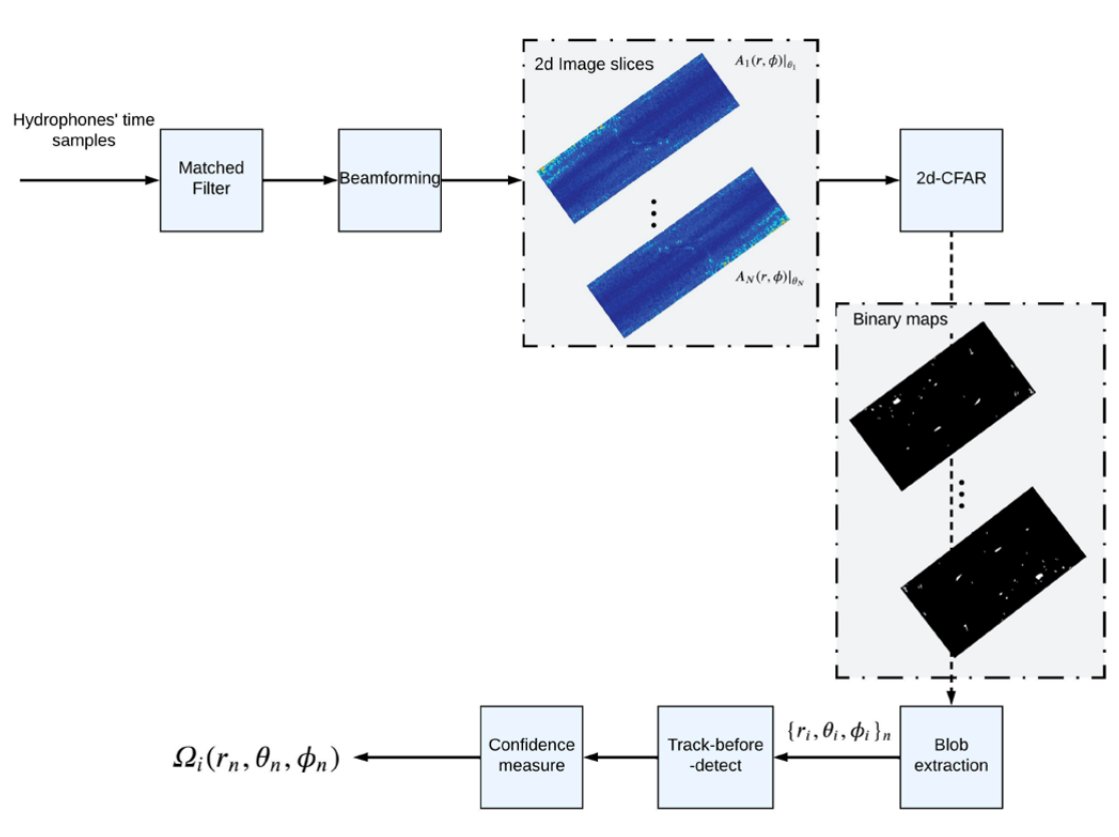


Fig. 16: Block diagram for the acoustic detection process.

279 is used here to align the measurements with true north and to compensate for any pitch or roll
 280 angles of the floater. Beamforming is performed after the matched-filter operation to compensate
 281 for the expected low clutter-to-noise ratio (CSR). The resulting 3D matrix is then clustered to
 282 find blobs of moving targets, which are the input for a Kalman-based multi-target tracker in
 283 the context of track-before-detect filtering. A confidence measure declares detection based on a
 284 stability test. The process is illustrated in Fig. 16, taken from [32], where more details about the
 285 acoustic detection part are available.

286

V. FIELD EXPERIMENTS

A. Laboratory conditions

288 The operation of the floater was validated in laboratory conditions in the LABUST laboratory
 289 pool in Zagreb, Croatia. The floater was trimmed to be approximately neutrally in the pool, tied
 290 to a rope and released. It was then acoustically instructed to sink, maintain depth and surface
 291 within the available depth of 3 m (Fig. 17).

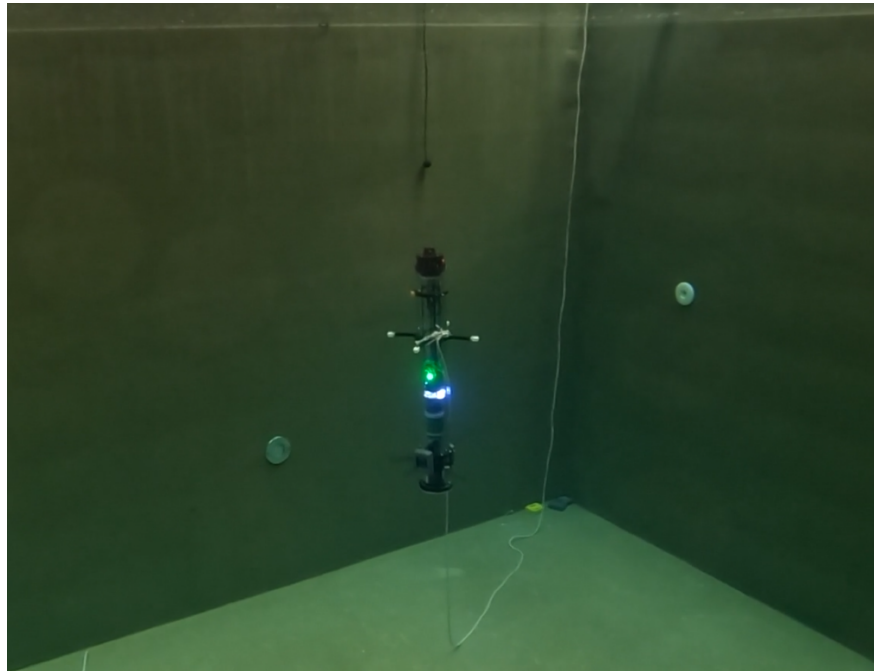


Fig. 17: SOUND floater performing depth-keeping in laboratory pool conditions.

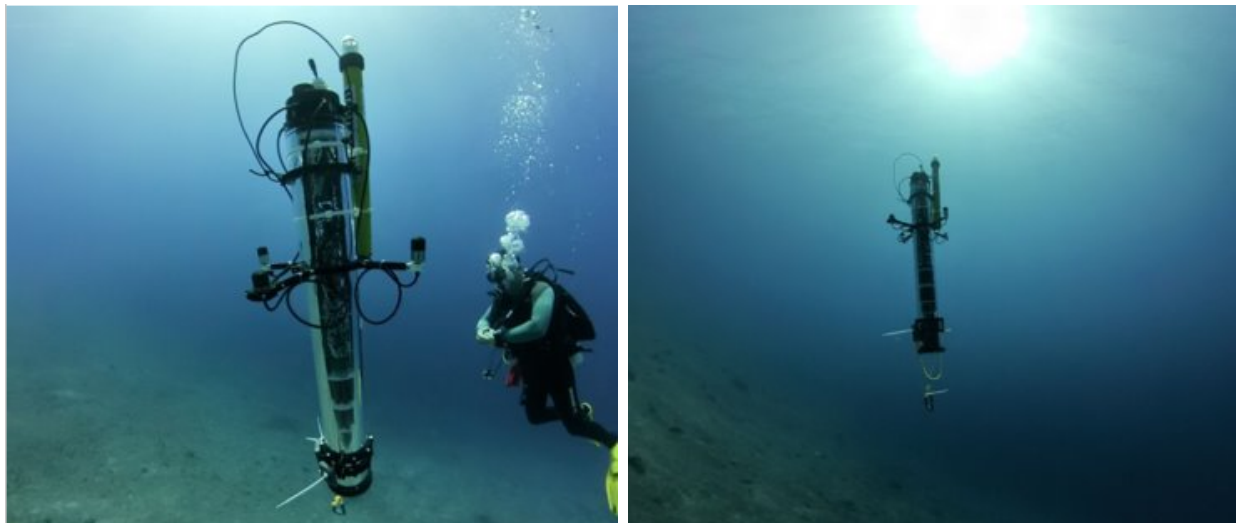


Fig. 18: A photo of the SOUND floater prototype at 20m depth deployed in Eilat, Israel, July 2023. Picture taken by Mr. Liav Nagar.

292 *B. Field Trials for Floater Design*

293 Two field trials were carried out to test the operation of the floater. To test the sensitivity to the
294 marine environment, two marine environments were considered: the Red Sea and the Adriatic

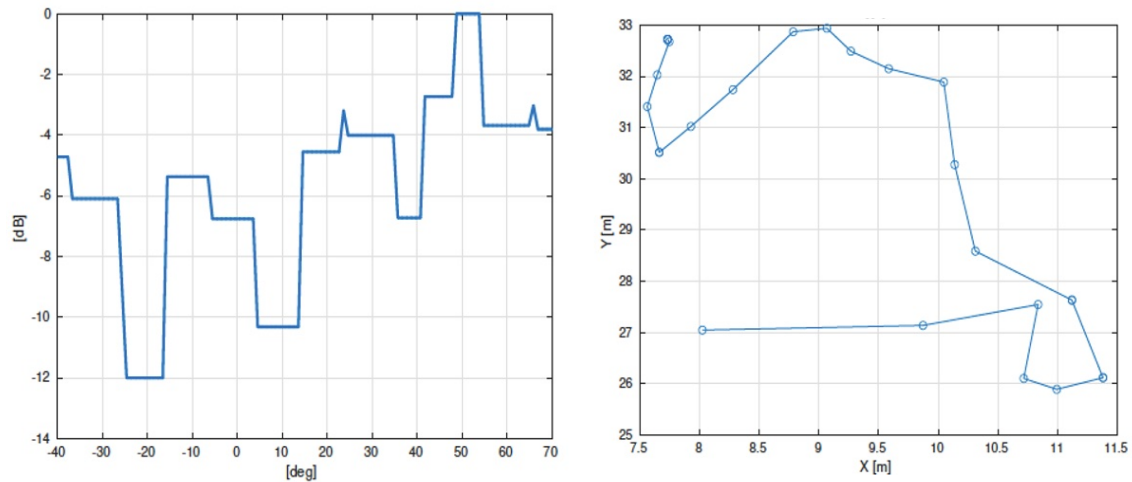


Fig. 19: Results of the acoustic detection tests in Eilat. Left panel: angle estimation. Right panel: location estimation. Track meets the location of the scuba diver with average error of roughly 5 m (against GPS).

295 Sea.

296 1) *Red Sea*: Sea trials were carried out in July 2023 to test floater operation under realistic
 297 conditions. After integration in laboratory facilities in Haifa, Israel, and a pressure chamber test
 298 for the required maximum depth of 50 m, field tests were conducted in Eilat, Israel, where the
 299 bathymetry is steep and allows easy access to a variety of depths (Fig. 18).

300 The field experiments included autonomous operation of a predefined mission. The floater was
 301 to maintain a specific depth for 30 minutes and then surface for recovery. Two divers followed the
 302 operation of the floater, and an operator on a pier remained in contact with the floater via acoustic
 303 communication. The deployment cycle (maintaining depth and then surfacing) was successfully
 304 completed. This mode of operation, including on-the-fly mission selection, will serve as the basis
 305 for the behavior of the SOUND floaters.

306 The experiment in the Red Sea for acoustic detection was conducted in 400 m water depth, an
 307 area with little fish population, to avoid unexpected targets. The floater was deployed to a depth
 308 of 12 m and kept at this depth. A pair of scuba divers served as targets. The position of the
 309 divers was monitored with a GPS logger attached to a small rubber buoy, which was attached
 310 to the divers with a fishing line. For safety reasons, the divers remained close to the vessel. The
 311 results of this operation are shown in Fig. 19 in terms of the angle estimate per chirp emission

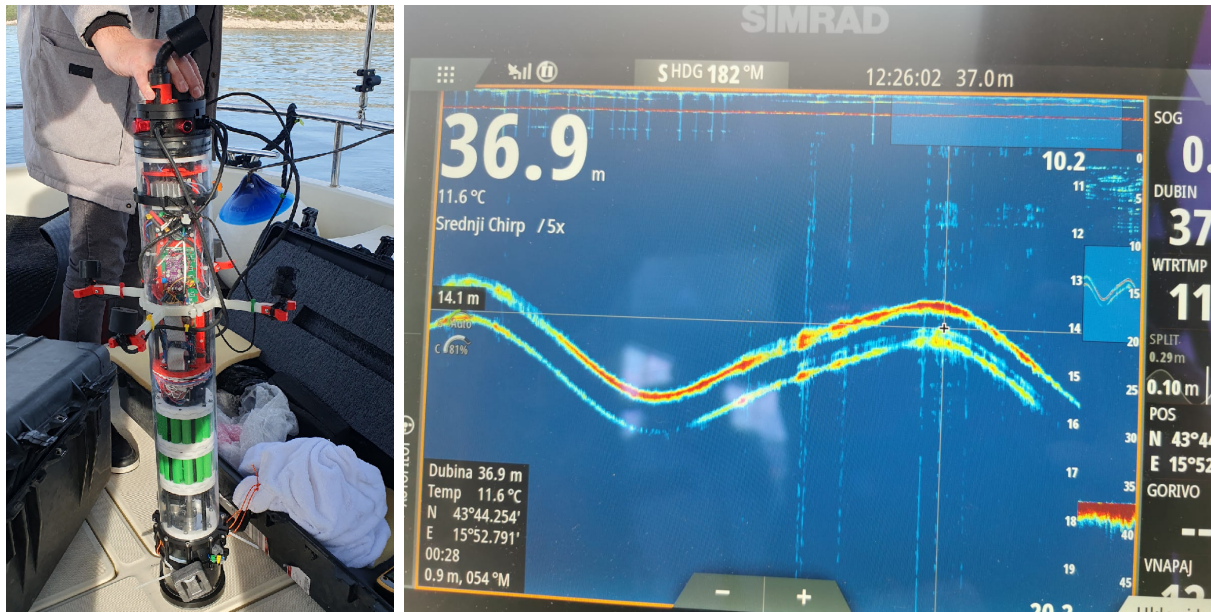


Fig. 20: SOUND floater prepared for deployment in Šibenik, Croatia, March 2024 (left). Floater oscillations around 15 m visible in the ship echosounder (right).

312 and the evaluated target trajectory (recall that our tracking is only performed on the horizontal
 313 plane). The track matched the diver's position with an average error of roughly 5 m.

314 2) *Adriatic Sea*: The acoustic detection in this sea experiment involved two target gilthead
 315 sea bream (*sparus aurata*) that were attached to buoys with a 20 m fishing line, similar to the
 316 pair of divers in the Red Sea experiment. A GPS logger was attached to each buoy to determine
 317 its position. Due to the length of the line to the fish, the GPS recording provided an accuracy of
 318 20 m for the true location of the fish. The two fish were released close to the floater and then
 319 swam freely without directional restriction. The floater was set to maintain its position at a depth
 320 of 20 m. The procedure lasted 10 min, after which the fish were released. Ethical approval for this
 321 experiment was obtained from the Ruđer Bošković Institute, Croatia, and the experiments were
 322 conducted in accordance with EU ethical regulations. The methods used followed the ARRIVE
 323 guidelines (<https://arriveguidelines.org>). The results of this experiment are analyzed in [32] and
 324 presented in Fig. 21 for completeness. Errors within the GPS accuracy are observed.

325 VI. CONCLUSIONS AND FUTURE WORK

326 In this paper, we have presented the design details of a working, low-cost Lagrangian floater
 327 prototype intended for in situ monitoring of fish populations. The floater has active acoustic

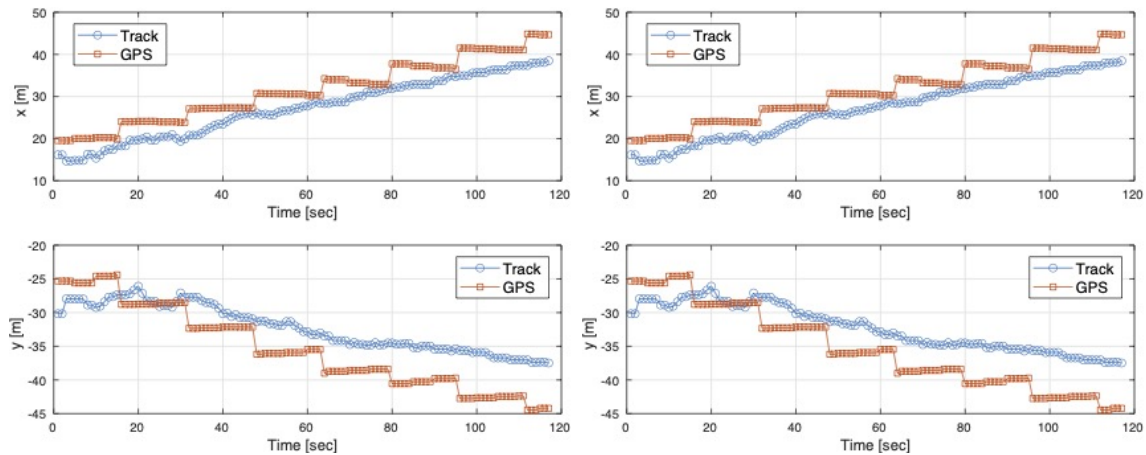


Fig. 21: Acoustic detection results from the experiment in the Adriatic Sea. Trajectory in the x-y plane estimated separately for two target fish swimming freely at the same time near the floater. Ground truth GPS-based location of the fish (20 m error) is marked in red.

328 detection capabilities and can profile the water column to a depth of 50 m or maintain depth while
 329 scanning its surroundings for schools of fish up to 500 m away. The prototype has been tested
 330 both in a laboratory pool and under field conditions. The buoyancy mechanism was redesigned
 331 with a focus on increasing robustness and replacing DC motors with stepper motors for more
 332 precise position control. Analysis of acoustic detection revealed several fish trajectories that
 333 were consistent enough to infer real targets. Finally, a long-term stress test of the floater will be
 334 conducted to ensure that it can meet the requirements for a 5-day operation.

335

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