

Self-reconfiguring modular robotic boats

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Self-reconfiguring aquatic robots offer promise for a wide range of marine applications, including building temporary infrastructure, remote maintenance and search-and-rescue operations, environmental monitoring, and on-demand transportation. However, achieving autonomous water-based self-reconfiguration, even in two dimensions on the water surface, remains challenging, due to complex nonlinear hydrodynamics, disturbances from self-motion and neighboring robots, as well as external environmental factors. Here, we present the *FloatForm* platform, a group of miniature modular robotic boats capable of self-assembling into physically connected structures, self-reconfiguring, and collectively traveling as larger assemblies via a hybrid coordination framework. Each robot unit is equipped with onboard sensing, motion control, and the ability to coordinate and physically connect with its neighbors. We demonstrate the feasibility of aquatic self-reconfiguration via hybrid coordination, where distributed controllers on each robot handle coordination tasks such as aggregating into desired shapes and avoiding collisions, while a minimalist central planner oversees the overall success of each task and fixes final imperfections. This work advances the design, control, and coordination of modular robotic systems in aquatic environments, enabling flexible, robust, and scalable applications on the water.

Modular self-reconfigurable robot (MSRR) systems^{1–17} consist of multiple robot modules that can connect and collaborate to form larger, adaptable robotic structures. A key feature of these systems is their ability to self-reconfigure, allowing modules to rearrange their connections to create structures adaptable to variable tasks and environments^{18,19}. Such systems hold particular promise in harsh aquatic environments where remote operations, like maintenance of sea-based structures, search-and-rescue missions or the construction of temporary floating infrastructures, require adaptability, robustness, speed and resource-efficiency. MSRR systems really come into their own with scale: a large number of robots means systems that are able to perform a wide range of tasks with versatility and robustness, with large numbers being able to compensate for local failures or shape imperfections. However, with larger numbers also comes increased

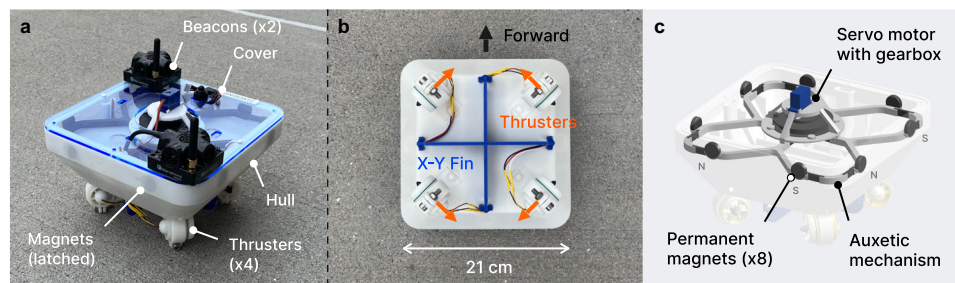
complexity. These complexities are further exacerbated in the aquatic domain, where remoteness, unreliable localization data, and unpredictable environmental conditions can hamper shape-formation, reconfiguration and collective group movements.

Recent advances have demonstrated a variety of successful implementations of MSRR systems on the ground and in the air^{18,20–29}, employing diverse coordination structures tailored to their operational domains. The Kilobot project demonstrated large-scale two-dimensional (2D) shape self-assembly with over 1000 robots²⁰, using a distributed algorithm that leverages simple local rules such as edge-following, gradient formation, and localization via infrared light sensing. This approach prioritizes scalability and robustness through simplicity, enabling massive swarms to self-organize using only neighbor-to-neighbor interactions. Roombots^{21–23} demonstrated

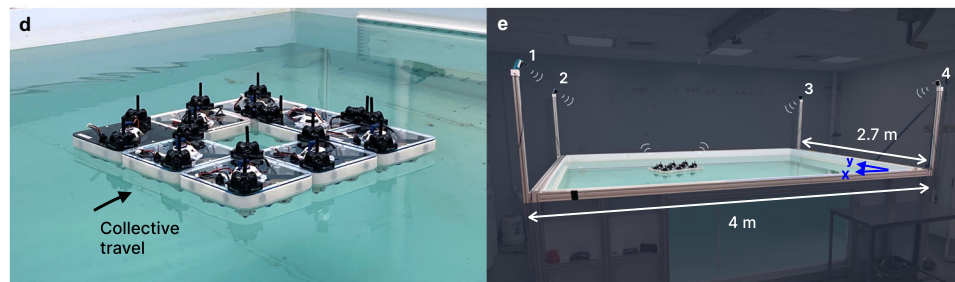
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FloatForm robot module



Experimental setup



Scenarios

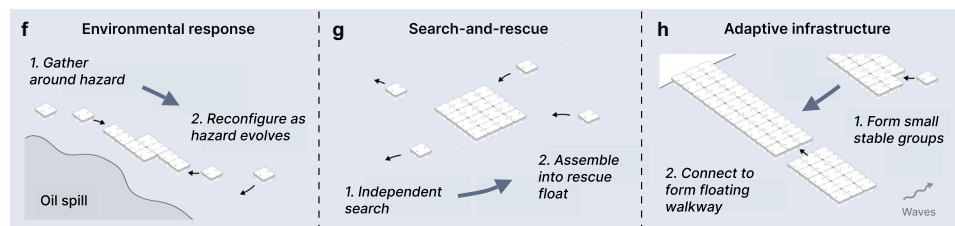


Fig. 1 | Modular FloatForm platform. **a** An overview of a single *FloatForm* module, including a 3D-printed hull, customized miniature thrusters, ultrasonic beacons, Inertial Measurement Unit (IMU), and an enclosed magnetic latching system based around an origami-inspired mechanism. **b** Bottom view of a single robot, highlighting the thruster arrangement and stabilizing ‘cross’ fin, to increase rotational inertia. **c** The origami-inspired latching mechanism to actuate the permanent magnets. **d** Eight *FloatForm* modules after self-assembly, moving in formation. **e** Illustration of the experimental setup, featuring four fixed ultrasonic beacons

positioned at the corners of the test pool (dimensions: $4.0 \times 2.7 \times 1.2$ m); these fixed beacons, analogous to GPS satellites, are elevated one meter above the water surface to ensure maximal coverage. **f–h** Potential applications of self-assembling and reconfiguring robot boat swarms: monitoring and containing an environmental hazard; a search-and-rescue mission with boats searching independently and coming back together to form a raft; building adaptive, resilient infrastructure in remote areas while exposed to environmental disturbances like waves and currents.

modular furniture that moves, self-assembles, and self-reconfigures in 3D. Here, the system employs offboard centralized optimal planning frameworks to coordinate complex reconfiguration sequences. While effective, the computational cost of global planning could limit real-time scalability, with search times increasing significantly beyond small module counts. The M-Blocks project^{24,25} introduced a novel hardware system that uses pulses of angular momentum and magnetic hinges to move modules and self-assemble 3D structures. The M-Blocks execute decentralized locomotion and can perform path-following, line formation, and gradient aggregation autonomously, while also accommodating centralized planning when global coordination is beneficial. This architectural flexibility allows M-Blocks to balance local autonomy with global task objectives. The SMORES-EP modular robots¹⁸ further illustrate the potential of hybrid architectures, combining centralized high-level mission planning with distributed module control and perception-driven reconfiguration. Thus, the SMORES-EP system is capable of dynamically adapting its morphology to previously unknown environments. In the air, MSRR systems face additional challenges of real-time stabilization and dynamic assembly. A group of flying robots, ModQuads, illustrated self-assembly and collective flight²⁷ through a hybrid coordination strategy. Here, centralized trajectory planning computes collision-free paths for docking maneuvers, while distributed flight controllers stabilize individual modules and

maintain formation after assembly. These works show the potential of hybrid architectures to enable complex behaviors while maintaining real-time responsiveness. However, in several of these systems^{18,21–25,27}, motion planning and coordination remain centralized, limiting scalability and requiring continuous communication with an offboard planner. By contrast, water-based MSRR systems remain in their infancy despite offering unique potential for ocean exploration, adaptive transportation, and dynamic marine infrastructure^{30–34}. Such systems could form on-demand shape-changing platforms to support offshore operations, ranging from environmental response and search-and-rescue operations to adaptive infrastructure (Fig. 1g, h). The ability to disassemble and self-reconfigure offers flexibility, minimizes ecological footprints and enhances logistical efficiency. Analogous behaviors can be observed in nature, for instance, red fire ants that dynamically self-assemble into floating rafts to survive seasonal flooding^{35,36}. Emulating this strategy, aquatic MSRR systems could autonomously form stable, cohesive structures to endure extreme maritime conditions. However, deploying MSRR systems in aquatic environments introduces a distinct set of challenges. Self-reconfiguration in open water requires real-time control over complex, nonlinear hydrodynamics, which are compounded by persistent disturbances from self-induced motion, inter-module interactions, and external forces like waves, currents, and wind. Operating modular

Table 1 | Qualitative comparison between aquatic MSRR systems

Feature	Paulos et al. (2015)	Gheneti et al. (2019)	FloatForm (Proposed)
Swarm capabilities	Self-assembly	Self-reconfiguration	Both
Control architecture	Centralized	Centralized	Hybrid
Planning complexity	Polynomial $O(n^3)^*$	Exponential (NP-Hard) **	Linear $O(k)^{***}$
Execution strategy	Batch sequential	Sequential	Parallel
Main computation platform	Central computer	Central computer	Onboard computers

FloatForm is a group of modular robotic boats capable of self-assembling and self-reconfiguring into physically connected structures. Reducing the reliance on centralized planning by leveraging a hybrid framework, FloatForm advances research on decentralization and self-organization of MSRR systems in the aquatic domain.

* n is the number of docking available slots, a subset of total swarm size N .

**MIQP complexity grows exponentially with the number of integer variables (binary collision constraints).

*** k is the number of local neighbors, independent of total swarm size N .

robot swarms in dynamic aquatic environments is challenging, as the conditions frequently undermine control, coordination, and alignment. To counter this, robust control architecture, fault-tolerant docking, and effective aggregation methods are essential. Given the environmental disturbances and unreliable localization and communication, individual robots must possess high autonomy to manage uncertainties. We believe the best solution for aquatic swarms is often a hybrid architecture that allows local autonomy while retaining a centralized coordinator to step in for unforeseen issues. Moreover, a crucial operational requirement is for robots to use global position data for long-range navigation and use local coordination and position negotiation for group tasks. This hybrid control framework significantly boosts the system's robustness for remote and complex operations. Success in these areas is essential to deploying modular aquatic robots at scale.

Several MSRR systems have explored self-assembly in aquatic environments, with early demonstrations highlighting the potential of robotic boats to autonomously form floating platforms. These systems have advanced the field of aquatic MSRR research and contributed essential insights into docking mechanisms and formation control^{32,33,37,38}. Paulos et al. presented a comprehensive system for automated assembly of large marine structures, using centralized planning algorithms to compute optimal collision-free trajectories and assign robots sequentially to docking sites on an assembly frontier. Their approach demonstrated large-scale coordination, including the assembly of a bridge with 33 modules. Addressing the complexity of reconfiguration maneuvers, Gheneti et al. developed centralized optimization methods to compute collision-free trajectories for shapeshifting tasks. Most recently, the Modboat project explored collective locomotion, allowing arbitrary connected lattices of underactuated aquatic modules to swim as a single steerable vehicle. Despite these advances, existing aquatic MSRR systems remain constrained by their reliance on fully centralized coordination. Such architectures are inherently vulnerable to single-point failures, particularly in dynamic and uncertain aquatic environments where individual module malfunctions or communication loss can cascade into system-wide deadlocks. Centralized control also scales poorly, with computational burdens increasing rapidly with the number of units, posing fundamental challenges for real-time responsiveness and robustness. Moreover, current systems impose a sequential dependency on assembly and reconfiguration: agents must wait for the global planner to compute schedules and for specific docking sites to become active. This forces the majority of the swarm to remain idle, waiting for their turn to move. Consequently, they lack the capability for decoupled parallel coordination, defined here as the ability of the entire swarm to navigate simultaneously toward the target geometry using onboard, distributed decision-making.

To address these limitations, we present **FloatForm**, an aquatic MSRR platform operating under a hybrid control architecture that combines minimal centralized oversight with predominantly

distributed coordination and control (see Table 1). Each *FloatForm* module possesses onboard sensing, state estimation, control, and latching capabilities that facilitate autonomous assembly and reconfiguration. The architecture employs a lightweight centralized planner solely for sparse high-level tasks, specifically for the one-time assignment of discrete positions for final structure refinement. Conversely, real-time navigation behaviors, including swarm gathering toward the target geometry, are governed in a distributed fashion by onboard controllers. After initially receiving higher-level shape commands from a central computer or user, state information is exchanged locally, allowing each robot to continuously compute its motion based on the target shape and immediate neighbors. Critically, self-assembly and self-reconfiguration are executed through decoupled parallel coordination: all robots navigate simultaneously, continuously adapting to disturbances without waiting for centralized trajectory scheduling. This hybrid framework balances local autonomy with global oversight, enhancing the scalability and resilience of aquatic MSRR systems. We demonstrate the FloatForm system with eight physical robot modules and validate scalability through simulations with up to 64 modules.

Results

Modular aquatic robot design with active latching and feedback control

We have designed and fabricated a group of eight *FloatForm* robot boats, each measuring L (0.21 m) × W (0.21 m) × H (0.14 m), as a platform for studying self-assembly and self-reconfiguration in the aquatic domain. Each robot is an autonomous floating robot with onboard sensing, control, and actuators, giving the ability to autonomously achieve a desired state in the presence of surrounding disturbances. A key feature of each robot is its capability to reliably and rapidly latch to other units. Latching is particularly challenging in aquatic settings due to the need for a broad working range to compensate for unpredictable disturbances. An overview of the system and its potential applications is presented in Fig. 1.

The square footprint of the *FloatForm* modules (Fig. 1a), enables flexible self-assembly into arbitrary square lattices. High maneuverability is critical for effective control and latching during coordination. To achieve this, four miniature thrusters are arranged in an “X” configuration (Fig. 1b, Supplementary Fig. 3), allowing for omnidirectional motion, including longitudinal and lateral translation, as well as on-the-spot rotation (see Supplementary Video 1). Stability during dynamic maneuvers is enhanced by strategically arranging internal components (like the battery) to maintain a low center of gravity and aligning these with the center of buoyancy. To compensate for the inherently low rotational inertia of the robot, a set of stabilizing fins (visible in the bottom view, Fig. 1b) is incorporated along the x and y axes. These fins increase hydrodynamic drag, reducing rotational actuation sensitivity at near-zero speeds and improving controller performance.

To enable reliable self-assembly and self-reconfiguration on the water, each robot must be capable of physically connecting (‘latching’)

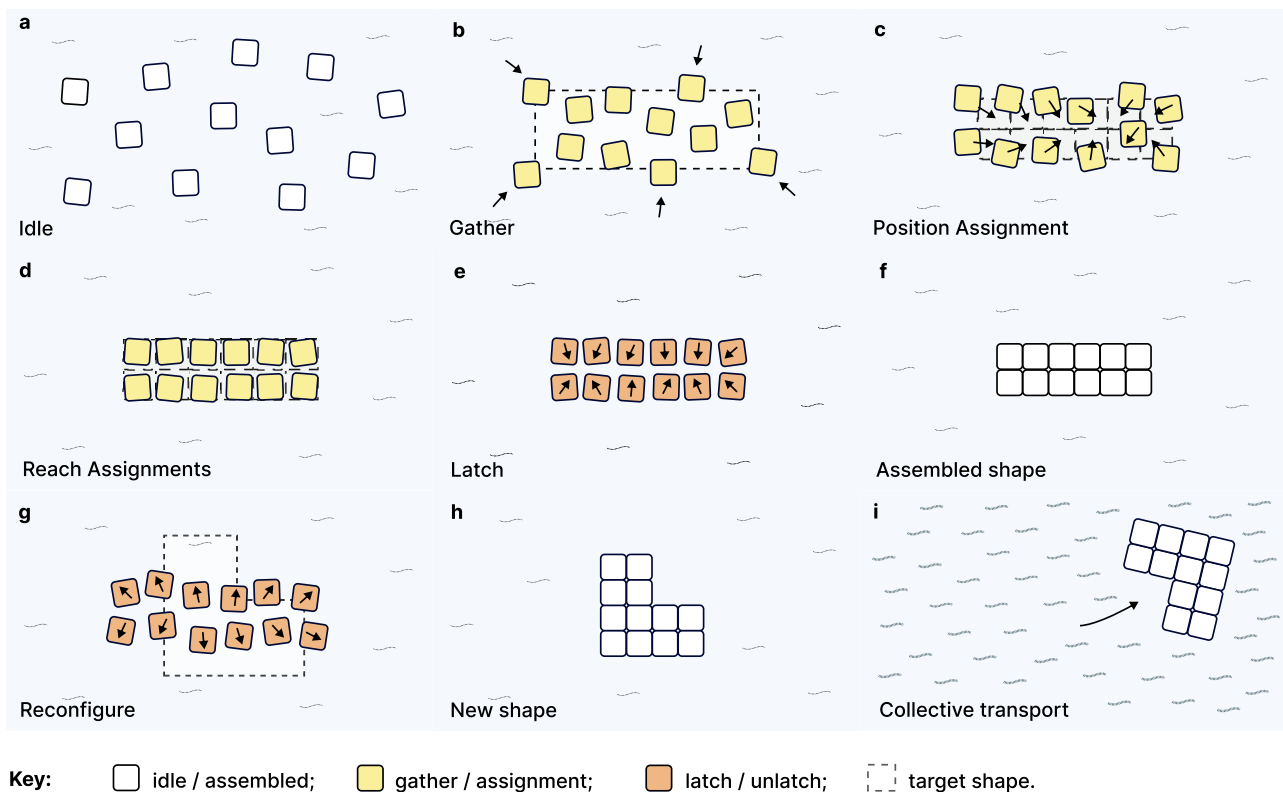


Fig. 2 | Algorithmic steps towards self-assembly, self-reconfiguration, and collective transport in an aquatic 2D MSRR system. **a** *FloatForm* modules remain idle or perform independent tasks while awaiting a shape command. **b** Upon receiving a new target shape, boats navigate toward the target configuration using a shape-reference formation algorithm. **c** Once in proximity of the desired shape, discrete positions are assigned via the Hungarian algorithm. **d** Robots proceed to

their designated positions using a position-reference formation algorithm. **e** Magnetic latching systems are activated to secure connections between neighboring units. **f** The structurally cohesive assembly. **g** A new shape command is received, the boats disassemble, repeating steps (a–f) to reconfigure into a new target configuration. **h** Completion of the reassembly process into the new shape. **i** The newly assembled structure moves collectively to a new destination.

with neighboring boats. To achieve this, a fully enclosed magnetic latching system was designed with the goal of reliably connecting with other boats even under disturbances. An origami-inspired mechanism allows a single servo motor located in the center of the robot to simultaneously actuate permanent magnets on all four sides of the robot (Fig. 1c, Supplementary Fig. 1). Permanent magnets are arranged by alternating polarity, with two magnets per side (Supplementary Fig. 1 and Supplementary Fig. 2a), ensuring boats can latch reliably across 10–15 cm gaps, without the added weight or sustained power draw of electromagnets. A custom 3D-printed gearbox is integrated, allowing the use of a simple, lightweight servo motor and adding sufficient mechanical inertia for the system to maintain either a latched or unlatched state without any power draw (Supplementary Figs. 1, 2, Supplementary Video 2).

The *FloatForm* robots utilize off-the-shelf acoustic beacons for self-localization. Figure 1e shows four stationary ultrasonic beacons located at the corners of the test pool, providing fixed reference points (analogously to GPS satellites). Each robot is equipped with two mobile beacons, enabling precise inference of position and heading (see Fig. 1a and Supplementary Fig. 4). Localization is achieved by estimating the propagation delay of ultrasonic pulses relative to the stationary beacons (Time-Of-Flight), which is then processed using a trilateration algorithm. To enhance accuracy and provide high-frequency state estimation, a Kalman filter integrates the data from the beacons with inertial measurements from the onboard IMU, yielding a refined estimate of the robot's pose, velocity, and acceleration.

The design of low-level motion controllers for the *FloatForm* modules is driven by the unique challenges of aquatic environments,

including nonlinear hydrodynamics and disturbances arising from self-motion or neighboring units. To address these challenges, each robot is equipped with a low-level feedback controller running on an embedded computer. The controller regulates the reference heading angle and ensures precise velocity control in surge and sway directions. The control architecture is based on a combination of Proportional-Integral-Derivative (PID) control and feedback linearization, effectively compensating for aspects of the robot's nonlinear dynamics and disturbances (see more details in Methods and Supplementary Note 2).

The *FloatForm* hardware has been designed with a focus on modularity, robust latching, onboard sensing, and feedback control. A detailed overview of the hardware design and control strategies is provided in the Methods section and Supplementary Materials. In the current study, we showcase the capabilities of the *FloatForm* system using a fleet of eight robotic units (Fig. 1d) that autonomously self-assemble and reconfigure into various two-dimensional structures within a controlled freshwater tank measuring 4.0 m × 2.7 m × 1.2 m (Fig. 1e). All two-dimensional trajectories are recorded for post-experimental analysis.

Self-reconfiguring robotic boats

As a collective of robot modules, the *FloatForm* system is designed with three fundamental capabilities: (i) self-assembly, facilitating the parallel formation of physically connected structures; (ii) self-reconfiguration, enabling the swarm to disassemble and reassemble into new physically connected configurations in parallel; and (iii) collective transport, allowing an assembled swarm to navigate as a cohesive unit across the water. Figure 2 provides an overview of the

three collective capabilities of the aquatic 2D MSRR system. The self-assembly process unfolds through the sequence illustrated in Fig. 2a–f. Self-reconfiguration, illustrated in Fig. 2g, h, consists of self-disassembly (Fig. 2g) followed by reassembly (analogous to Fig. 2a–f, omitted for brevity). These processes can be dynamically deployed to accommodate various operational demands. Collective transport allows the assembled shape to move together as a unified whole toward a specified target (Fig. 2i). Additional details of the self-reconfiguration algorithms are available in Methods and Supplementary Note 3.

Figure 3 illustrates the task decomposition and information flow of the FloatForm system, which employs a hybrid coordination framework. It is clearly shown that a central coordinator running on a remote computer sends high-level commands (shape, latching actions, and group trajectory of collective transport) and fixes position imperfections, while each robot’s onboard computer handles low-level state estimation, motion control, and shape-formation algorithms to determine its position within the swarm. Robots exchange position information with their immediate neighbors directly via ROS communication framework.

Each FloatForm module operates with an identical code within the swarm. Initially, robots are randomly distributed across the water. Robots determine their positions and orientations using onboard

sensors described earlier in this section (also see more details in Supplementary Note 1). To initiate self-assembly, a target shape S , defined by a set of vertices, is transmitted to all robots within the swarm. The initial target shape is deliberately described as larger than the final desired configuration. The robots first gather and align within this preliminary shape using a distributed shape-reference formation algorithm based on potential field methods, incorporating attractive and repulsive forces. The attractive force guides the robots toward the target region, while the repulsive force mitigates collisions between robots (see more details in Methods). As most robots converge within the designated area, the shape progressively shrinks (Fig. 2b). This gradual reduction prevents congestion and enables the collective to transition smoothly into a configuration close to the final structure.

After completing the initial shape formation, minor misalignments may remain. To refine the structure, a centralized position assigner allocates new positions to the robots (Fig. 2c, Supplementary Note 3). A distributed position-reference formation algorithm then guides the robots toward their designated positions (Fig. 2d, Supplementary Note 3). Once all robots have reached their target locations, the magnetic latching mechanism engages, linking the modules into a rigid floating assembly (Fig. 2e, f). Following self-assembly, the collective may autonomously reconfigure in response to new shape commands issued by the task coordinator, or operate as a coherent

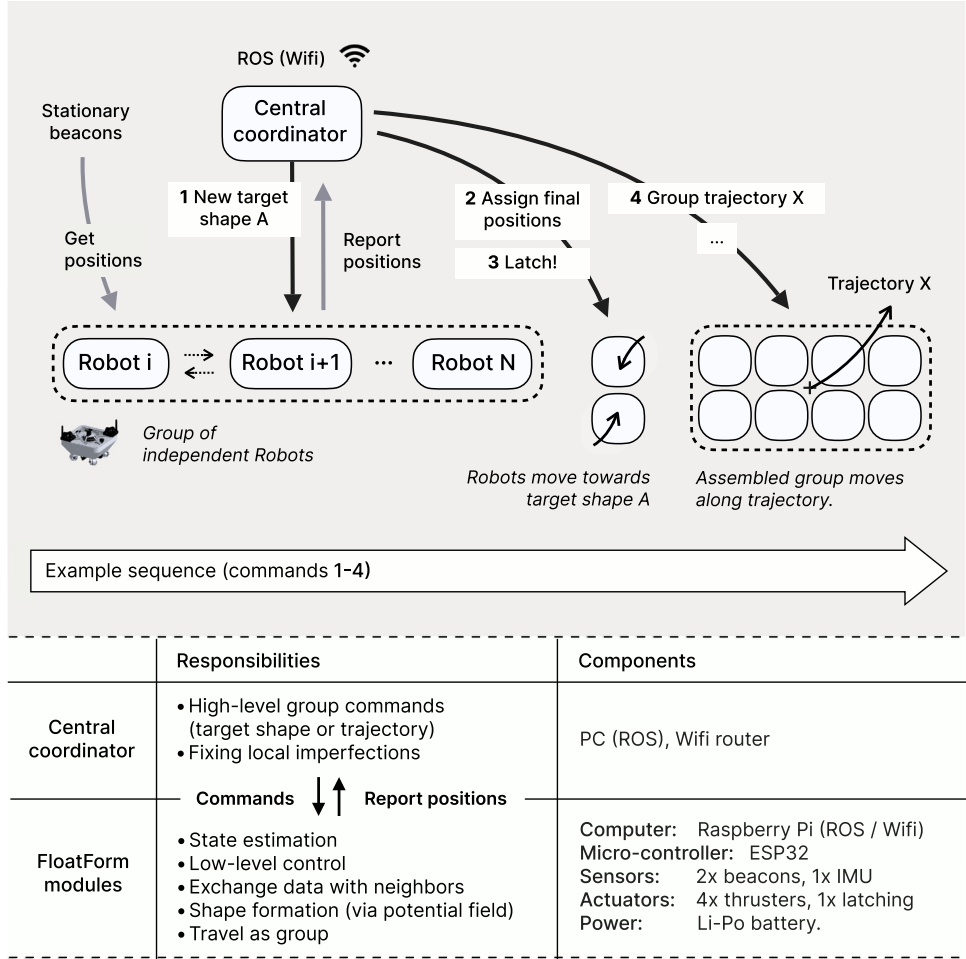


Fig. 3 | Task breakdown and communication in the FloatForm system. A central coordinator sends a high-level shape command to all boats, while individual robots handle their low-level state-estimation, motion control, and shape formation algorithms to compute their positions within the swarm. Robots compute their own potential fields and exchange position data with their immediate neighbors. The coordinator intermittently requests feedback from the robots on their

positions and finalizes position assignments before sending a global command to all robots to latch. To perform movements as a group, the coordinator sends a desired target trajectory to each robot of the assembled group, with each robot determining its own thruster control to match the desired overall trajectory of the assembly.

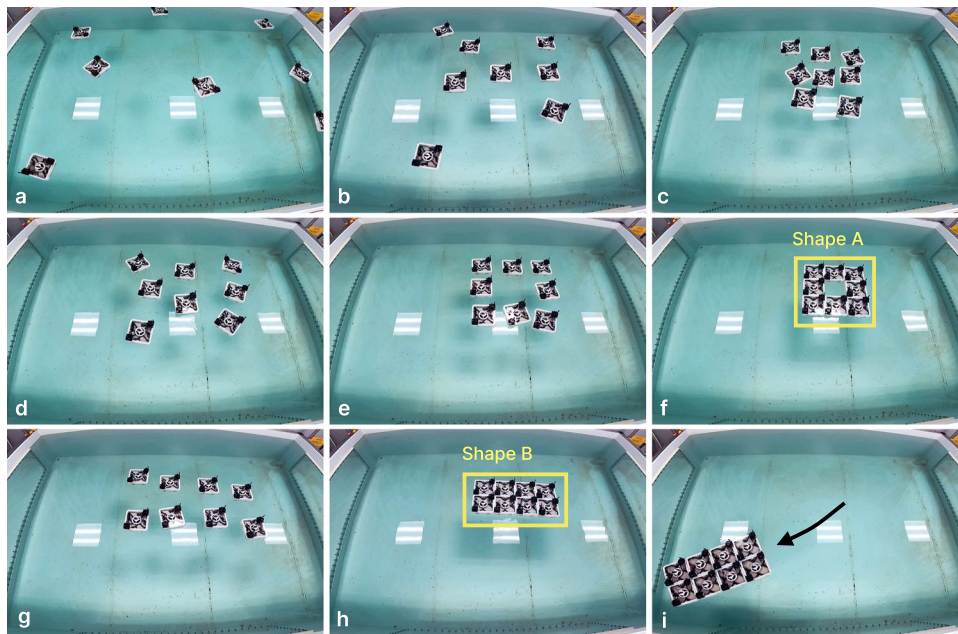


Fig. 4 | Self-reconfiguration experiments with eight FloatForm modules. **a** Idle robots awaiting a target shape command. **b, c** The robots begin gathering within the approximate boundary of a target shape, “A”. **d, e** Once the boats are within the boundary, discrete positions are assigned to each unit. **f** The boats then latch

together to form a rigid structure. **g** A new target shape, “B”, is received: the boats de-latch and the process repeats, as they reposition within the boundaries of shape “B”, where discrete positions are reassigned, and the boats latch into the new configuration (**h**). **i** The newly formed structure maneuvers to the side of the pool.

robotic system capable of executing collective transport tasks. If a new shape command is received, the self-reconfiguration process is initiated: the latching mechanisms disengage, decoupling robots from their neighbors, and repulsive forces in potential field methods push the robots apart (Fig. 2g). Once sufficiently dispersed, the robots reassemble into a new configuration using the same hybrid coordination strategy (Fig. 2h). We demonstrate collective transport following self-assembly (Fig. 2i). In this phase, each module is provided with center and orientation data of the goal shape, after which a position-reference potential field algorithm running on each robot calculates the attractive forces that determine the reference velocity and heading needed to steer each module to their assigned targets (see more details in Supplementary Note 3).

We validated this approach through experiments with four (Supplementary Video 3) and eight FloatForm modules (Figs. 4, 5, and Supplementary Video 4). As illustrated in Fig. 4, a group of eight robots successfully executed self-assembly, self-reconfiguration, and coordinated movement toward the corner of the tank. Each experiment required approximately 4–8 minutes. The corresponding trajectories of the robots are depicted in Fig. 5, clearly delineating each coordination phase. Across 10 experimental trials, the system achieved 90% and 70% success rates without human intervention in trials involving four and eight robots, respectively.

To further validate the framework’s scalability and robustness to environmental disturbances beyond the physical constraints of the laboratory, we conducted extensive simulations with up to 64 modules, the details of which are provided in Supplementary Note 4 and Supplementary Videos 5, 6.

Discussion

Self-reconfiguring aquatic robots offer promising potential for scalable environmental monitoring and rapid infrastructure deployment. However, realizing this potential requires overcoming the complex hydrodynamics and persistence disturbances inherent to the domain. To address these challenges, we have introduced FloatForm, a modular robotic system that explores a hybrid, predominantly distributed coordination approach for aquatic assembly.

Our architectural approach represents a new framework in contrast to existing aquatic MSRR strategies. The aquatic domain presents a distinct challenge defined by persistent environmental disturbances. Thus, FloatForm adapts the hybrid paradigm to this domain by employing decoupled parallel coordination. This architecture decouples motion planning from centralized frameworks, allowing the entire swarm to navigate simultaneously toward the target shape. Unlike previous aquatic systems that impose a sequential dependency, where agents must wait for a central planner to schedule trajectories or for specific docking sites to become active, our approach allows for concurrent navigation of the entire swarm.

This decentralization is critical for scalability. Existing centralized aquatic systems rely on global optimization algorithms that scale poorly with swarm size. By adapting distributed swarm formation algorithms to approximate a square lattice topology, we reduce the planning complexity from a global polynomial of the swarm size (e.g. $O(N^2)$ or $O(N^3)$)³², to a local constant-time operation ($O(k)$ based on detected neighbors). This reduction renders scalable coordination computationally feasible on resource-constrained modules, eliminating the reliance on offboard central stations and enabling the swarm to operate almost independently. Table 1 contains a qualitative comparison with other aquatic MSRR systems. Conceptually, our coordination strategy aligns more closely with distributed swarm formation algorithms³⁹, than with traditional MSRR motion planners. Standard distributed shape formation algorithms produce geometries unsuited for mechanical connection, or at least for grid-like formations. We bridge the gap by adapting these fully distributed swarm behaviors to approximate a square lattice topology, using a sparse centralized assignment step triggered only to refine a lattice shape that purely distributed methods cannot guarantee.

Our simulations with 4, 8 (Supplementary Video 5) and 64 agents (Supplementary Video 6) confirmed that this framework scales effectively without computational saturation, while results under modeled current disturbances validated that the continuous feedback controller can provide necessary drift compensation. In hardware, our successful indoor demonstrations establish a foundation for real-time hybrid control, though they also highlighted critical challenges arising

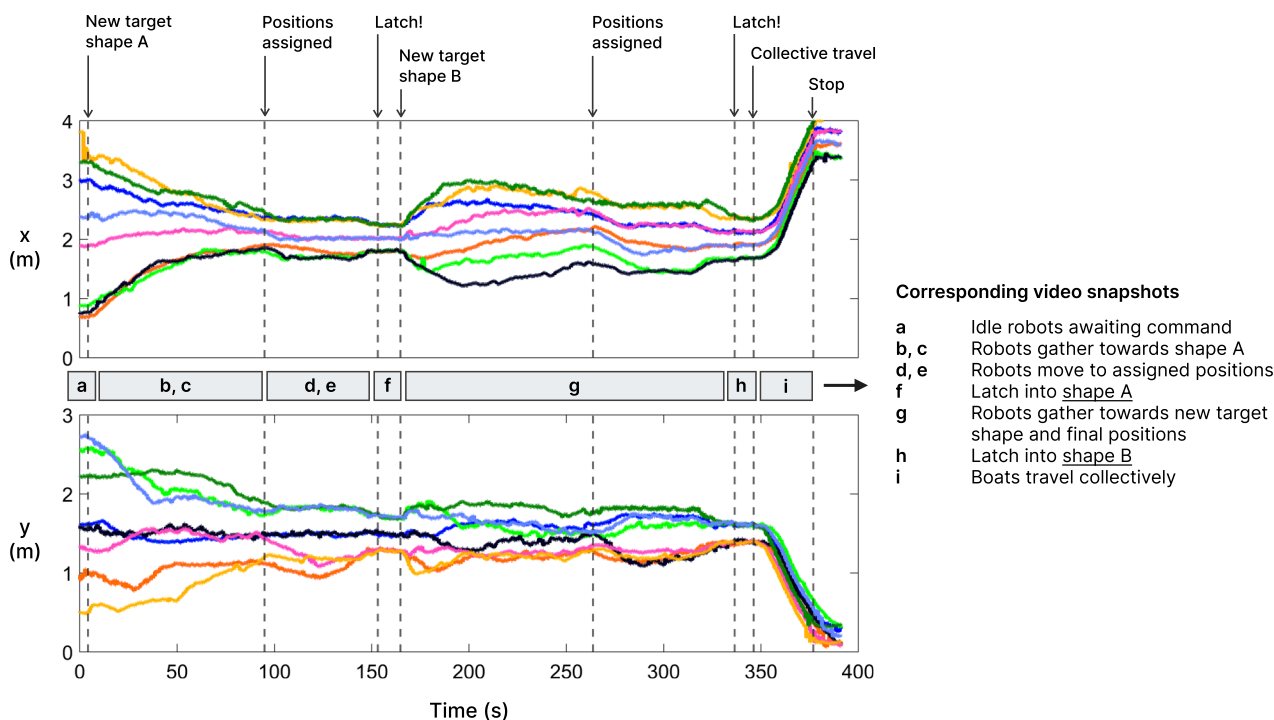


Fig. 5 | FloatForm module trajectories during self-assembly and reconfiguration. The X and Y trajectories of eight *FloatForm* robots during the self-reconfiguration experiments shown in Fig. 4 and Supplementary Video 4, high-

level commands to the boats are annotated at the top. The symbols “a–i” correspond to the phases of self-reconfiguration shown in Fig. 4 and are defined on the right side of the figure.

from model uncertainty and hardware limitations. Current limitations include occasional failure modes, including algorithmic deadlocks, such as robots becoming trapped in local minima during shape formation. These deadlocks are presently resolved using stochastic perturbations, wherein robots ‘shake’ themselves free and retry latching (Supplementary Video 7). To enhance the reliability and efficiency of shape formation control, future efforts will replace the existing potential-field heuristic with an optimization-based control barrier function (CBF) approach⁴⁰. This strategy is anticipated to provide stronger convergence guarantees and minimize error-prone behaviors during formation. However, applying CBFs to this domain is non-trivial, as it requires developing a theoretical framework to translate the competing objectives (shape containment, inter-agent collision avoidance, and rigid lattice alignment) into compatible barrier functions and Quadratic Programming formulations. Additional failure modes stemmed from physical constraints: limited thruster resolution at low speeds occasionally degraded controller performance on some agents. Similarly, acoustic interference within the confined test setup caused intermittent localization loss. Crucially, however, hybrid framework demonstrated architectural resilience: once a ‘lost’ agent recovered its signal, it autonomously rejoined the structure without causing a system-wide halt. To address this, hardware nonlinearities and ensure robust navigation in realistic outdoor environments, we propose to leverage learning-based control techniques, such as data-driven Model Predictive Control (MPC)⁴¹, which would allow robots to adapt in real time to changing conditions, obstacles, and noisy sensory inputs. Furthermore, we have demonstrated that, once assembled, the *FloatForm* swarm can execute coordinated movements as a single unit under calm conditions. However, maintaining stable collective motion in the presence of disturbances and minimal inter-robot communication remains an open challenge³¹.

Transitioning to open-water deployment will require further mechanical and sensing adaptation. Increasing the robot size could improve hydrodynamic stability and enable a broader range of tasks, which in turn calls for more robust latching systems capable of

withstanding higher loads⁴². Although the current latching mechanism demonstrated robust performance at the present scale, its operation under stronger wave-induced motion has not yet been established. Addressing such conditions will likely require both mechanical scaling and further refinement of the latching design. On the sensing side, the current study used a fixed ultrasonic beacon system for localization in a controlled indoor environment, which was suitable for validating the platform and control framework but is not directly applicable to open-water settings. Replacing the current acoustic indoor localization system with outdoor-capable technologies such as GPS, vision-based tracking, or Doppler Velocity Logs will be essential to drive each *FloatForm* inside the shape region. Simultaneously, short-range relative sensors (such as acoustic⁴³ or infrared-based sensing) will be necessary for the interactions between boats. This ensures that collision avoidance and precise latching remain high-frequency, low-latency, and decoupled from global localization errors. Robust onboard power and communication systems, potentially incorporating solar charging and distributed networking, will also be critical for sustained missions in remote environments.

Ultimately, this work underscores the transformative potential of robotic collectives in the maritime domain. By combining minimal centralized oversight with largely distributed autonomy, *FloatForm* enables countless applications. Looking ahead, we envision collective aquatic robotic systems performing tasks across a broad range of maritime applications, including forming temporary platforms for infrastructure inspection or maintenance. In oceanographic research, reconfigurable robot formations could enable adaptive sensor networks for studying migratory species or monitoring environmental changes. In offshore logistics and emergency response, modular robotic teams could function as reconfigurable docking stations or transport units for use in inaccessible areas. *FloatForm* draws some inspiration from biological systems such as fire ants, which dynamically self-assemble into rafts and bridges to survive floods and cross gaps^{35,36}. These natural swarms achieve robust collective behaviors through local rules and physical interactions, allowing the colony to

adapt to complex, unpredictable environments without predominant centralized control. Similarly, our system demonstrates that through minimal centralized coordination and largely distributed autonomy, robotic collectives can exhibit flexible self-assembly and self-reconfiguration in aquatic environments. This perspective underscores the promise of future aquatic swarm systems: resilient, reconfigurable, and capable of operating in the dynamic and uncertain conditions of the real world.

Methods

FloatForm module design

The *FloatForm* hardware was designed with ease of fabrication and programming in mind, making it quick to assemble and conduct experiments involving larger numbers of robots. The hull, thrusters, and latching mechanisms are the core mechanical components. A square footprint was chosen, allowing boats to assemble into square lattices (Fig. 1). The manufacturing process consisted of resin-based 3D printing: hull and four thruster brackets, which hold the custom miniature thrusters (Fig. 1a), and laser-cutting of an acrylic top-plate. The thrusters, while compact, produce large forces (at low resolution) relative to the vehicle's overall inertia, resulting in aggressive rotational motions at near-zero speeds. To compensate, a basic set of fins were added along the x and y axes of the boats (Fig. 1c), increasing the hydrodynamic drag and facilitating less sensitive angular control at low speeds. Finally, a laser-cut acrylic cover protects the electronics from occasional water-splashes, while providing a supporting structure for the ultrasonic beacons and access points for battery charging via USB and a power switch. The current *FloatForm* design achieves 2D motion with a forward speed of 70 mm/s and near-zero turning radius around its center of mass.

To facilitate shape reconfiguration, each *FloatForm* robot must be capable of reliably latching and de-latching with other boats. The designed magnetic latching system is fully enclosed within the hull of the boat and makes use of an origami-inspired mechanism to simultaneously actuate permanent magnets on all four sides of the robot via a single lightweight servo motor located in the center of the robot (see Supplementary Fig. 1 and Supplementary Fig. 2a). The mechanism is based on a uniformly-scaling rotating polygon⁴⁴, with rotation at the center causing auxetic contraction of all four sides (Supplementary Fig. 2b). The auxetic mechanism is composed of rigid 3D printed elements (PLA 3D printed on a Prusa Mk3 desktop FDM printer) with simple strips of synthetic rubber forming the compliant hinges. In the extended position (see Supplementary Fig. 2c), the magnets are in contact with the interior sides of the hull, allowing other boats in the working range (10 cm), to latch to the sides (see Supplementary Fig. 2e). When de-latching, the mechanism is rotated, pulling the magnets inwards (see Supplementary Fig. 2b) and breaking attraction to neighboring robots (see Supplementary Fig. 2d). Magnets are arranged with alternating polarities, ensuring boats reliably latch into square lattice formations. The combined inertia of the mechanism and a 3D printed gearbox ensures that either latched or unlatched states can be maintained with no power to the motor (power is only required to change state).

More details of the mini thruster design, electronics and sensors, and the robot localization can be found in Supplementary Note 1.

Low-level feedback control

The precise maneuvering of individual *FloatForm* modules in accordance with high-level planning objectives requires the implementation of feedback control. This approach enables the system to dynamically adapt to varying reference commands and sensor inputs, ensuring accurate steering adjustments for each robot. Here, we develop feedback controllers based on proportional–integral–derivative (PID) control to regulate each *FloatForm* robot's three degrees of freedom: surge, sway, and yaw. To account for nonlinear dynamics, we further

employ feedback linearization. Additionally, given the constraints on the customized thruster's rotational speed and the over-actuated nature of the vehicle, a thrust allocation strategy is designed to distribute control commands optimally across the thrusters.

The surge and sway speed controller can receive reference velocities (u_d, v_d) from a user/operator or a higher-level algorithm. In this case, the references are provided by a higher-level algorithm for shape formation and reconfiguration. Considering that τ_u represents the force in the surge direction, and τ_v the force in the sway direction, velocity controllers can be designed following a PID-based approach as:

$$\tau_u = K_{pu}e_u + K_{iu} \int e_u d\tau + K_{du}\dot{e}_u \quad (1)$$

$$\tau_v = K_{pv}e_v + K_{iv} \int e_v d\tau + K_{dv}\dot{e}_v \quad (2)$$

where $e_u = u_d - u$, $e_v = v_d - v$ are the velocity errors, u is the surge velocity, v is the sway velocity, and $K_{pu}, K_{iu}, K_{du}, K_{pv}, K_{iv}, K_{dv}$ are positive controller gains. With such controllers, the robots can follow time-varying reference velocities for any feasible task.

The heading control system is designed based on a cascade approach. First, the heading error is chosen as $e_\psi = \psi_d - \psi$, where ψ is the robot heading angle, and the desired heading ψ_d is a user-defined parameter, or dependent on the desired shape formation. Then, the high-level PID is designed as:

$$r_d = K_{p\psi}e_\psi + K_{i\psi} \int e_\psi d\tau + K_{d\psi}\dot{e}_\psi \quad (3)$$

where r_d is the desired yaw rate, and $K_{p\psi}, K_{i\psi}, K_{d\psi}$ are positive controller gains. Now, consider the following nonlinear model in yaw using Fossen's equations of motion for marine systems⁴⁵:

$$\dot{r} = \frac{1}{I_z - N_r} ((-X_{\dot{u}} + Y_{\dot{v}})uv + N_r r + N_{r|r} r|r| + \tau_r) \quad (4)$$

Here, r is the rotational speed, τ_r is the rotational moment, I_z is the moment of inertia, and $X_{\dot{u}}, Y_{\dot{v}}, N_r, N_{r|r}, N_{\dot{r}}$ are hydrodynamic parameters. Then, the model can be rewritten as:

$$\dot{r} = f_r(r) + g_r(r)\tau_r \quad (5)$$

where $f_r(r)$ and $g_r(r)$ are defined as follows:

$$f_r(r) = \frac{(-X_{\dot{u}} + Y_{\dot{v}})uv + N_r r + N_{r|r} r|r|}{I_z - N_r} \quad (6)$$

$$g_r(r) = \frac{1}{I_z - N_r} \quad (7)$$

Next, applying a change of variable $\tau_r = u_r$, and feedback linearization, the low-level yaw controller can be designed based on a PD approach as:

$$u_r = \frac{1}{g_r(r)} (K_{pr}e_r + K_{dr}\dot{e}_r - f_r(r)) \quad (8)$$

with error $e_r = r_d - r$, and positive controller gains. Implementing feedback linearization allows us to compensate for nonlinear dynamics terms, which have a large effect on the yaw degree of freedom.

A detailed description of the thrust allocation is provided in Supplementary Note 2.

Hybrid coordination algorithm

The proposed hybrid coordination algorithm combines a lightweight centralized planner for high-level tasks, such as position assignments to refine shape formation, with distributed controllers onboard each robot to govern core behaviors, including shape formation and collision avoidance. We demonstrate three fundamental collective capabilities: (i) self-assembly, enabling the parallel formation of physically connected structures; (ii) self-reconfiguration, allowing the swarm to disassemble and reassemble into new physically connected configurations in parallel; and (iii) collective transport, enabling the assembled swarm to navigate cohesively across the water. As illustrated in Fig. 2, each collective capability consists of multiple sequential phases. For the gathering phase (Fig. 2b), a distributed shape-reference formation algorithm is implemented to drive the swarm gradually into the desired shape and a square lattice structure.

More specifically, the algorithm is based on the Artificial Potential Field method³⁹, which establishes so-called potential forces to control a system. Two main potential forces are considered in this work, an attractive force ($F_a \in R^2$) and a repulsive force ($F_r \in R^2$):

$$F_p = k_{p,1}F_a + k_{p,2}F_r \quad (9)$$

where $k_{p,1}, k_{p,2}$ are positive weighting parameters. Here, the attractive force is designed to drive the *FloatForm* robot to the desired region, whereas the repulsive force is applied to avoid collisions and create lattices between neighboring robots. First, let us consider the attractive force. The vehicle is given a desired shape, constructed by a matrix $V = [v_1, v_2, \dots, v_W]^T$, composed by the shape vertices $v_w \in R^2$, where $w = 1, 2, \dots, W$, and W is the total number of vertices. Next, a variable s is equal to 1 if a module is inside the shape, and -1 if the vehicle is outside the shape. Then, a distance vector d is evaluated with the robot position $p = [x, y]^T$ and its nearest vertex v_{nearest} as $d = v_{\text{nearest}} - p$. The attractive regional force is computed as

$$F_a = k_{a,1}s \left(1 + \tanh\left(\frac{s||d||}{k_{a,2}}\right) \right) \left(\frac{d}{||d||} \right) \quad (10)$$

where $k_{a,1}, k_{a,2}$ are positive parameters. Now, let us consider the repulsive force, which is composed of a collision element $F_c \in R^2$ and a lattice element $F_l \in R^2$, for each neighboring module:

$$F_r = \sum_{n=1}^N (F_{c,n} + F_{l,n}) \quad (11)$$

with N as the total number of neighbors.

More specifically, for each neighboring module, $F_{c,n}$ and $F_{l,n}$ are computed with:

$$F_{c,n} = k_{r1} \left(\frac{r_0}{||r_n||} - \left(\frac{r_0}{||r_n||} \right)^2 \right) \left(\frac{r_n}{||r_n||} \right) \quad (12)$$

$$F_{l,n} = \frac{-\sin(4\varphi_n)}{||r_n||} \left(\frac{r_n}{||r_n||} \right) \quad (13)$$

where $\varphi_n = \text{atan2}(y_n - y, x_n - x)$ is the angle between the robot and the neighbor n , $r_n = p_n - p$ is the distance between the robot and the neighbor n , $p_n = [x_n, y_n]^T$ is the position of a neighboring module, and $k_{r,1}, r_0$ are tuning parameters. Finally, since the potential field force F_p is computed in the inertial reference frame, it is rotated into the body frame with:

$$[u_d, v_d]^T = R(\psi)^T F_p \quad (14)$$

and its rotation matrix

$$R(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{bmatrix} \quad (15)$$

Finally, $[u_d, v_d]^T$ are saturated to user-defined maximum allowed velocities and then sent as desired values to the robot's surge and sway speed controller. This formulation naturally separates sensing requirements. The attractive force requires only the robot's own position in a global frame. This information can be provided by the acoustic beacons indoors, GPS outdoors, or by any other similar technology. The repulsive forces depend only on the relative positions and bearing to neighboring agents, which can be obtained from short range sensors such as cameras, acoustic ranging, or even LiDAR, independent of global localization. This sensor-agnostic design enables the same control algorithm to operate across different deployment environments by substituting only the sensing modalities, not the coordination logic.

Further details of the other phases of the algorithm such as the centralized task assignment and collective transport algorithm, as well as the computational complexity are provided in Supplementary Note 3.

Data availability

The data that support the findings of this study are available in figshare with the identifier <https://doi.org/10.6084/m9.figshare.31975389>.

Code availability

All the data analyses were performed using custom scripts written in MATLAB 2024b. All codes to support the findings of this study are available in figshare with the identifier <https://doi.org/10.6084/m9.figshare.31975395>.

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Author contributions

W.W., N.H., C.R. and D.R. proposed the research and conceptual design of the FloatForm system. W.W. and N.H. designed hardware (hull design, latching mechanism, custom thrusters) and electronics. W.W. and A.G. developed robot control and software. W.W., A.G., N.H., and D.R. conducted the experiments. All authors analyzed and visualized data and contributed to the writing of the paper.

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Competing interests

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