

A closed-loop engineering framework for rapid development of unmanned maritime systems using integrated digital and additive technologies

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ABSTRACT

This study presents a closed-loop engineering methodology for the rapid development of unmanned maritime systems by integrating 3D scanning, reverse engineering, digital optimization, additive manufacturing, subsystem integration, and experimental validation within a unified feedback-driven workflow. Unlike existing manufacturing-oriented closed-loop and digital twin approaches, the proposed methodology connects the complete engineering lifecycle through continuous interaction between digital models and physical prototypes.

The methodology was validated through two complementary case studies representing reverse- and forward-engineering development scenarios: a modular UAV platform and a coastal monitoring buoy. Comparative engineering workflow assessment indicated an estimated 30–50% reduction in overall prototype development effort and a 35–40% reduction in component-level redesign activity, while ICP-based evaluation of selected representative UAV components showed maximum geometric deviations of 0.5–1.5 mm. Functional validation further confirmed subsystem operation and structural performance under the investigated test conditions.

The proposed methodology extends feedback beyond manufacturing-stage optimization to the complete engineering lifecycle, providing an adaptable engineering approach for rapid prototyping, iterative engineering refinement, and modular development of unmanned maritime systems and related cyber-physical engineering applications.

1. Introduction

Recent advances in 3D scanning and additive manufacturing have significantly transformed engineering processes by enabling rapid geometric acquisition, digital reconstruction, and accelerated prototype fabrication [1–4]. These technologies are increasingly adopted in maritime engineering, where unmanned aerial vehicles (UAVs) and unmanned surface vehicles (USVs) require rapid customization, modular architectures, and efficient integration of sensing, communication, and control subsystems [5–7].

In parallel, digital twins and artificial intelligence have expanded engineering capabilities through real-time monitoring, predictive analysis, and adaptive optimization [8–11]. Hybrid digital twin architectures [12,13] and closed-loop manufacturing control [14] further demonstrate the potential of feedback-driven engineering.

Despite these advances, existing studies remain focused on

individual engineering stages and rarely integrate reverse engineering (RE), digital optimization, additive manufacturing (AM), subsystem integration, and experimental validation within a unified engineering lifecycle for unmanned maritime systems.

To address this gap, this paper proposes a closed-loop engineering framework integrating 3D scanning, reverse engineering, digital optimization, additive manufacturing, sensor integration, and experimental validation into a unified iterative workflow. Unlike existing manufacturing-oriented closed-loop and digital twin approaches, the proposed methodology connects the complete engineering lifecycle through continuous feedback between digital models and physical prototypes.

The framework was validated through two complementary case studies representing reverse-engineering and forward-engineering development scenarios, demonstrating its applicability to rapid development of unmanned maritime systems.

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The main contributions of this work are:

- a unified closed-loop engineering framework integrating 3D scanning, reverse engineering, digital optimization, additive manufacturing, sensor integration, and experimental validation;
- a repeatable feedback-driven engineering methodology supporting continuous design refinement throughout the development lifecycle;
- experimental validation using two complementary engineering platforms representing reverse-engineering and forward-engineering development scenarios;
- comparative engineering workflow assessment indicating reduced overall prototype development effort and component-level redesign activity relative to conventional sequential engineering workflows.

The proposed methodology was developed to bridge the gap between isolated digital engineering technologies and an integrated engineering lifecycle for rapid development of unmanned maritime systems.

Unlike conventional industrial products, unmanned maritime platforms operate in highly dynamic environments that require continuous adaptation of structural components, payload configurations, sensing modules, and communication subsystems. Consequently, engineering feedback extending across the complete development lifecycle is essential for rapid redesign, iterative validation, and mission-specific customization.

2. Background and related work

3D scanning technologies, including laser scanning, structured light, and photogrammetry, enable rapid acquisition of high-density point clouds for digital reconstruction of complex engineering objects (Jandyal et al., 2022; [15]). Reverse engineering transforms these datasets into parametric CAD models through mesh generation and surface reconstruction, supporting redesign, quality inspection, digital twins, and reconstruction of legacy components [16]. Recent studies further integrate reconstructed models into hybrid digital twin environments with real-time synchronization [12,13]. However, these approaches remain largely separated from downstream engineering activities such as design optimization, fabrication, and experimental validation.

Additive manufacturing has become a key technology for rapid prototyping and customized production using processes such as Fused Deposition Modelling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) [3,17]. Recent studies introduced intelligent monitoring and closed-loop control through image-based defect detection [14] and hybrid digital twins integrating process simulations with real-time sensing [12,13]. Nevertheless, these developments remain focused on manufacturing-stage optimization and do not integrate reverse engineering, design optimization, subsystem integration, and experimental validation within a complete engineering workflow.

Unmanned aerial and surface platforms are increasingly employed for surveillance, search and rescue, environmental monitoring, and infrastructure inspection [5–7]. Their operation in dynamic maritime environments requires rapid structural adaptation, modular architectures, and efficient subsystem integration [10,11]. However, engineering workflows for these platforms remain largely sequential, limiting rapid iteration and continuous engineering refinement.

Digital twins and artificial intelligence have significantly expanded engineering capabilities through virtual modelling, real-time monitoring, predictive analysis, and adaptive optimization [8]. Hybrid digital twin architectures combining physical sensing with numerical simulations have recently been demonstrated for additive manufacturing [12, 13], while AI-based approaches improve sensor-data analysis and object detection in unmanned systems [9]. Despite these advances, existing implementations remain focused on individual functions and rarely establish continuous feedback connecting digital models, physical prototypes, and iterative engineering development.

2.1. Research gap

Recent studies established closed-loop mechanisms for additive manufacturing through automated defect detection [14] and hybrid digital twin architectures integrating sensing with process simulation [12,13]. However, these approaches remain confined to manufacturing-process supervision and do not integrate reverse engineering, CAD reconstruction, engineering redesign, subsystem integration, and experimental validation within a unified engineering lifecycle.

Consequently, existing approaches lack an end-to-end methodology integrating geometric acquisition, digital modelling, fabrication, physical implementation, and iterative refinement for unmanned maritime systems. The proposed methodology addresses this gap through a unified feedback-driven engineering workflow (Table 1).

3. Proposed closed-loop engineering framework

3.1. Concept of closed-loop engineering

Conventional engineering workflows separate design, manufacturing, and testing into sequential stages, limiting iterative prototype refinement. In contrast, closed-loop engineering establishes continuous feedback between digital models and physical systems. In this work, it is defined as an integrated methodology combining data acquisition, reverse engineering, digital optimization, additive manufacturing, subsystem integration, experimental validation, and iterative feedback within a unified engineering workflow.

3.2. Architecture of the proposed framework

The proposed framework comprises nine interconnected stages forming a continuous engineering workflow (Fig. 1). Depending on the application, the workflow may begin either with reverse engineering of an existing physical object or with the development of a native CAD model. After the initial digital-representation stage, both pathways proceed through digital optimization, additive manufacturing, subsystem integration, experimental validation, and feedback-driven design refinement. The engineering stages of the proposed framework are described in the following subsections.

3.2.1. Object identification

Selection of the engineering object according to operational requirements and mission objectives.

3.2.2. 3D scanning

Acquisition of geometric data using a Scantech SIMSCAN 30 handheld laser scanner for subsequent digital reconstruction.

3.2.3. Point cloud processing

Filtering, registration, and noise removal using Statistical Outlier Removal (SOR), Radius Outlier Removal (ROR), and Iterative Closest Point (ICP) registration algorithms in CloudCompare v2.13.2.

3.2.4. Reverse engineering

Conversion of processed point clouds into editable parametric CAD models using QuickSurface v8.0.93 and SolidWorks 2024 SP0.

Table 2 summarizes the implementation of each stage of the proposed closed-loop methodology, including the associated input data, processes, engineering outputs, technologies, and representative implementation in the two case studies.

3.2.5. Digital optimization

Optimization of geometry, weight, manufacturability, and subsystem interfaces.

Table 1
Comparison of existing approaches and the proposed framework.

Representative Study	Core Technologies	Integration Level	Feedback Mechanism	Maritime Applicability	Key Limitations
Tanasi et al. [16]	3D scanning, CAD	Component	None	Partial	No downstream integration
Daneshmand et al. [3]; Kumar et al. [17]	FDM, SLA, SLS	Manufacturing	Local process feedback	Not domain-specific	Manufacturing only
Ahsan et al. [8]	Digital twins, closed-loop AM	Digital-physical	Real-time process and digital synchronization	Limited	No reverse engineering
Behseresht et al. [14]	Closed-loop FDM	Manufacturing	Automatic defect detection and adaptive G-code parameter correction	Limited	Print-quality control only
Park et al. [13]	Hybrid digital twin	Digital-physical	Real-time synchronization between physical sensors and virtual process simulation	Limited	AM process only
Love et al. [12]	Hybrid digital twin, AI	Digital-physical	Continuous synchronization, predictive monitoring, adaptive manufacturing control	Limited	Manufacturing-stage focus
Atanasov and Iliev [9]	AI, sensor fusion	Data layer	Data-driven feedback	Limited	No engineering lifecycle
Proposed framework	3D scanning, RE, AM, optimization, sensors	Complete lifecycle	Lifecycle-wide	High	Integrated engineering workflow

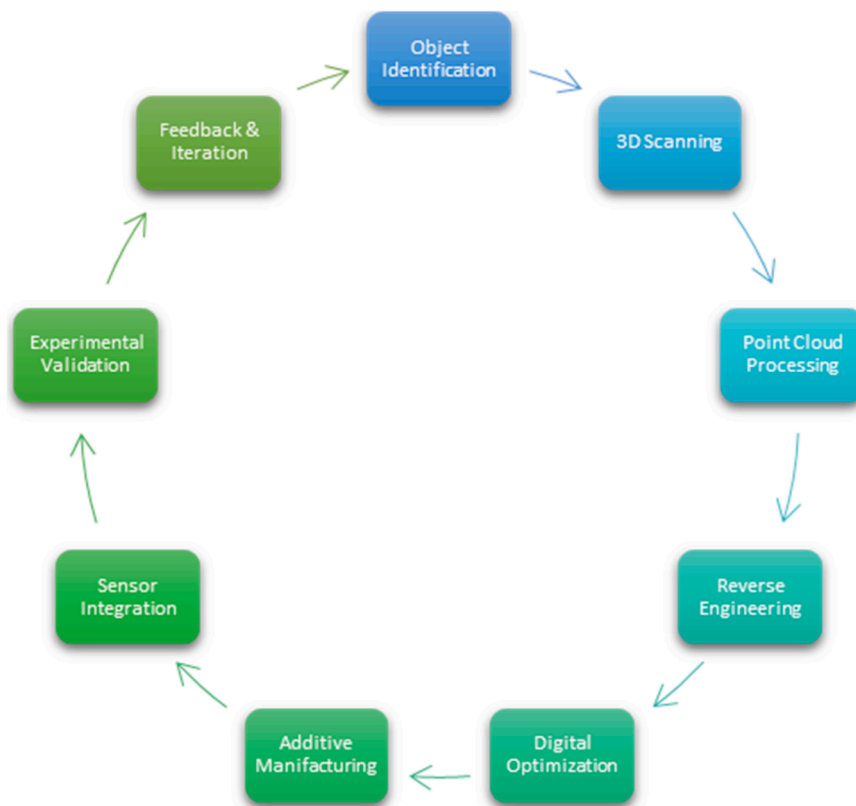


Fig. 1. Architecture of the proposed closed-loop engineering framework.

3.2.6. Additive manufacturing

Fabrication of optimized components using FDM technology on FlashForge Creator 5 Pro, Epitum JL, and MakerBot Replicator+ systems.

3.2.7. Sensor and system integration

Integration of sensing, communication, and control subsystems for both validation platforms.

3.2.8. Experimental validation

Laboratory and field validation of structural integrity and subsystem functionality.

3.2.9. Feedback and iteration

Experimental observations are incorporated into subsequent CAD revisions, enabling iterative refinement.

4. Framework validation through two engineering case studies

4.1. Validation strategy

The proposed closed-loop engineering framework was validated through two complementary case studies representing reverse- and forward-engineering scenarios for unmanned maritime systems, building on prior engineering development of unmanned platforms in the maritime environment [18]. The first involved reverse engineering of a modular UAV platform, whereas the second focused on CAD-based

Table 2

Engineering stages of the proposed closed-loop methodology.

Stage	Input Data	Process Description	Output	Tools / Technologies	Representative Implementation
Object Identification	Operational requirements, mission objectives	Definition of system purpose and constraints	Target object, system specification	Engineering analysis, domain knowledge	UAV and buoy platform selection
3D Scanning	Physical object	Geometric data acquisition	Raw point cloud	Scantech SIMSCAN 30	UAV frame scanning; post-fabrication scanning of selected buoy components and mating interfaces
Point Cloud Processing	Raw point cloud	Filtering, alignment, and noise removal (SOR, ROR, ICP)	Registered point cloud	CloudCompare v2.13.2	UAV reconstruction and geometric assessment of selected buoy interfaces
Reverse Engineering	Processed point cloud	Mesh reconstruction and parametric CAD conversion	Parametric CAD model	QuickSurface v8.0.93, SolidWorks 2024 SP0	Parametric CAD reconstruction
Digital Optimization	CAD model	Structural and manufacturability optimization	Optimized CAD model	SolidWorks 2024 SP0 (CAD)	Weight reduction and interface optimization
Additive Manufacturing	Optimized model (STL)	FDM-based fabrication	Physical prototype	FlashForge Creator 5 Pro, Epitum JL, MakerBot Replicator+	Prototype fabrication
Sensor and System Integration	Physical prototype	Sensor, communication, and control integration	Functional system	RGB/thermal cameras, GPS, IMU, environmental sensors	Subsystem integration
Experimental Validation	Functional system	Laboratory and field validation	Performance data	Laboratory and field-testing facilities	Flight and aquatic validation
Feedback and Iteration	Experimental data	Design refinement	Updated CAD model	CloudCompare v2.13.2, SolidWorks 2024 SP0, QuickSurface v8.0.93	CAD refinement

development of a modular coastal monitoring buoy.

The two case studies were selected to demonstrate the applicability of the proposed framework to both reverse-engineering and forward-engineering scenarios. Their implementation and validation are described in the following sections.

4.2. Engineering implementation of the proposed framework

This section describes the practical implementation of the proposed framework for the modular UAV platform and the coastal monitoring buoy. The software tools, hardware systems, manufacturing technologies, subsystem-integration activities, and validation procedures employed in the two case studies are presented in the following subsections.

The hardware, software, and configuration adopted throughout the implementation of the proposed framework are summarized in Table 3.

4.2.1. Geometric data acquisition

For the UAV case study, geometric data were acquired using a Scantech SIMSCAN 30 handheld laser scanner. Prior to data acquisition, the scanner was calibrated according to the manufacturer's standard calibration procedure.

Scanning was performed in Standard Mode using the manufacturer's recommended workflow and the accompanying DefinSight v1.2.2.7 software. Scan-specific parameters, including working distance, point

spacing, and acquisition resolution, were automatically managed by the software and were therefore not treated as independent experimental variables. The objective of this stage was accurate geometric reconstruction for reverse engineering rather than evaluation or optimization of scanner performance. For the coastal monitoring buoy, the initial geometry was developed directly in SolidWorks 2024 SP0 according to the functional, structural, and manufacturing requirements of the platform (Fig. 2).

Following fabrication, selected buoy components and mating interfaces were also scanned to assess geometric fit and support iterative design refinement, including representative features such as the cover and channel/groove interfaces.

4.2.2. Point cloud processing and reverse engineering

Raw point clouds were processed in CloudCompare v2.13.2 using Statistical Outlier Removal (SOR), Radius Outlier Removal (ROR), and Iterative Closest Point (ICP) registration before mesh reconstruction in QuickSurface v8.0.93 and parametric modelling in SolidWorks 2024 SP0. Standard implementations of the SOR, ROR, and ICP algorithms using the default CloudCompare v2.13.2 settings were employed throughout the study. For the UAV platform, point-cloud processing supported reverse engineering and CAD reconstruction, whereas for the buoy platform, scanning of selected fabricated components and interfaces was used to assess geometric fit and provide feedback for subsequent design refinement. The resulting digital models were subsequently used for structural optimization, design refinement, and additive manufacturing (Fig. 3).

4.2.3. Digital optimization

For the UAV case study, CAD reconstruction was performed in QuickSurface v8.0.93. Subsequent engineering redesign and optimization were carried out manually in SolidWorks 2024 SP0 using a feature-based CAD modelling approach. For the buoy case study, the native CAD model was developed and iteratively refined directly in SolidWorks 2024 SP0. The redesign process focused on improving manufacturability, subsystem integration, and maintainability. For the UAV platform, optimization included structural simplification, cable routing, and modular mounting interfaces, whereas the buoy design incorporated waterproof compartments, sealing interfaces, and dedicated sensor modules.

Table 3

Experimental Setup and Software Configuration.

Engineering Stage	Hardware / Software	Configuration
3D scanning	SIMSCAN 30	Factory calibration, Standard Mode
Point-cloud processing	CloudCompare v2.13.2	Default SOR, ROR and ICP settings
CAD reconstruction	QuickSurface v8.0.93	Standard reconstruction workflow
CAD design	SolidWorks 2024 SP0	Feature-based CAD modelling
STL preparation and slicing	Printiformer v1.1.1 / Orca-Flashforge v1.6.1 / MakerBot v4.10.1.2056	Manufacturer-recommended material profiles
FDM printing	FlashForge, Epitum, MakerBot	Default manufacturer material profiles



Fig. 2. Reverse- and forward-engineering entry points of the proposed methodology: (a) reverse engineering of the UAV platform; (b) forward engineering of the modular smart buoy.

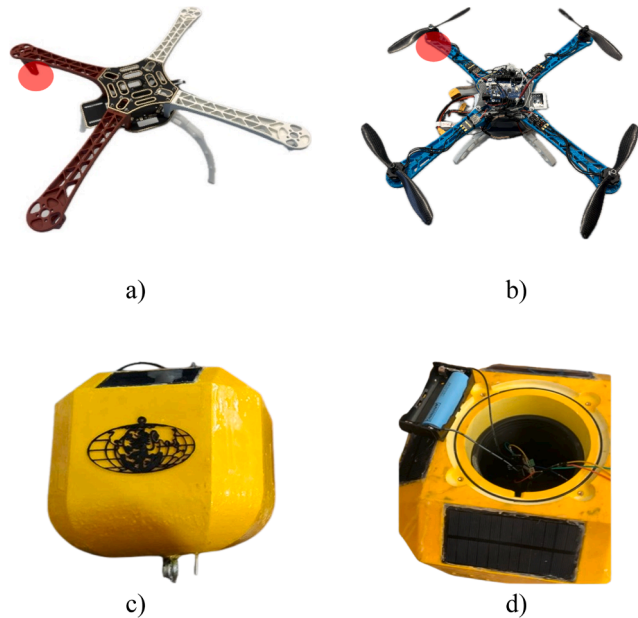


Fig. 3. Digital optimization of the two validation platforms: (a) original UAV frame; (b) optimized UAV structural component; (c) frame of the smart buoy; (d) internal view of the smart buoy.

4.2.4. Additive manufacturing

Optimized CAD models were exported as STL files and prepared for fabrication using Orca-Flashforge v1.6.1, MakerBot v4.10.1.2056 (for FlashForge Creator 5 Pro and MakerBot Replicator+) and Printiformer v1.1.1 (Epitum JL). Manufacturer-recommended material profiles were adopted without manual optimization of nozzle temperature, print speed, cooling, or acceleration parameters. The additive manufacturing stage focused on producing functional engineering prototypes for validation of the proposed framework. Accordingly, no additional printer-specific parameter tuning was performed, ensuring that the engineering evaluation reflected the proposed methodology rather than optimization of the FDM process (Figs. 4 and 5.)

The buoy was fabricated from PLA+ with 10% infill to balance buoyancy, structural rigidity, and material consumption. Printed components were sealed using environmentally friendly polymer and epoxy resin to improve waterproofing for marine operation. The materials selected for additive manufacturing and the engineering rationale for their selection are summarized in Table 4.

4.2.5. Assembly and sensor integration

The UAV integrated RGB and thermal cameras, Global Positioning System (GPS), Inertial Measurement Unit (IMU), and flight-control

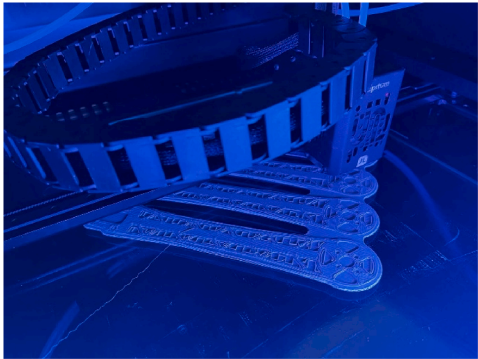


Fig. 4. FDM fabrication of customized UAV structural components.

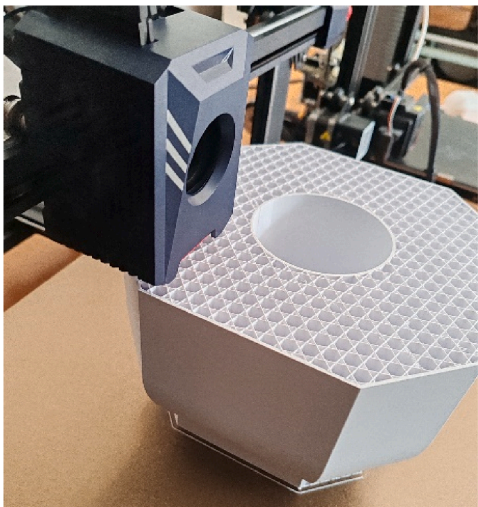


Fig. 5. FDM fabrication of the modular smart buoy housing.

Table 4 Material selection for the fabricated components.		
Component	Material	Reason
UAV frame	ABS	Higher impact resistance
Buoy housing	PLA+	Low weight and sufficient rigidity
Waterproof parts	PETG	Moisture resistance

electronics, whereas the buoy incorporated environmental sensing, communication, GPS, and autonomous power-management modules (Fig. 6). Both platforms adopted a modular architecture that simplifies maintenance. The integrated sensors were selected to demonstrate the

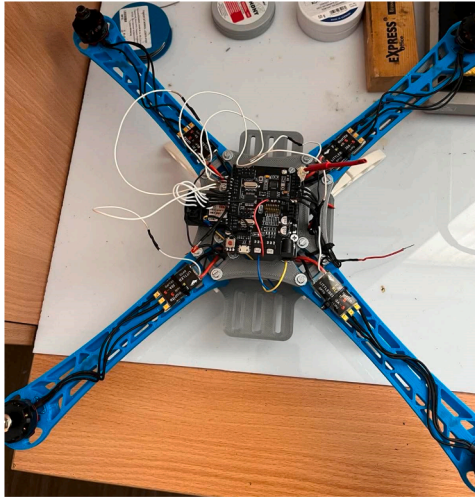


Fig. 6. Integrated UAV platform after subsystem assembly.

capability of the proposed framework to support modular payload integration rather than to evaluate the performance of individual sensing technologies.

4.2.6. Experimental validation and feedback

Preliminary flight experiments evaluated the flight stability, structural integrity, propulsion performance, subsystem functionality, and communication reliability of the UAV platform. The coastal monitoring platform was validated under laboratory and controlled aquatic conditions at the Sea Survival Centre and other dedicated experimental facilities of the Nikola Vaptsarov Naval Academy [19–21]. The validation programme included waterproofing, wave-tank stability, and communication tests under representative operating conditions. The collected experimental data were subsequently incorporated into the iterative design process. Representative validation activities are presented in Figs. 7–8.

Each validation activity was considered successful when the corresponding subsystem operated without functional degradation under the representative test conditions.

Experimental observations from both case studies were analysed to verify manufacturability, subsystem integration, and structural performance. The resulting feedback was incorporated into subsequent design



Fig. 7. Experimental modular UAV platform used during field validation trials [22].

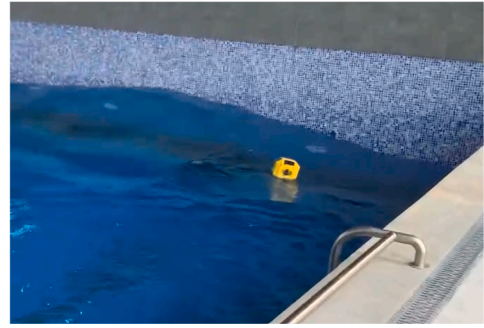


Fig. 8. Laboratory and controlled aquatic validation of the modular coastal monitoring platform at the Sea Survival Centre and dedicated testing facilities of the Nikola Vaptsarov Naval Academy.

iterations.

4.2.7. Feedback and design iteration

Experimental observations were incorporated into subsequent CAD revisions to improve manufacturability, subsystem integration, and maintenance. For the UAV, revisions optimized cable routing, electronic accessibility, and payload interfaces while preserving compatibility with the original DJI F450 structure. For the buoy, refinement focused on sealing interfaces, internal compartment organization, and sensor positioning.

For the UAV platform, the principal trigger for iterative redesign was structural weight reduction. Progressive reduction of frame mass enabled the use of batteries with lower capacity while preserving the required operational endurance. This, in turn, reduced propulsion requirements, allowing the implementation of smaller motors and associated electronic components. Consequently, each structural optimization generated additional opportunities for reducing system weight, manufacturing cost, and overall platform complexity without compromising functionality.

This optimization strategy simultaneously reduced manufacturing cost, propulsion power requirements, energy consumption, and overall platform mass while increasing the available payload capacity for additional sensing modules required for maritime surveillance and environmental monitoring.

Rather than correcting manufacturing defects, the feedback mechanism continuously optimized the complete engineering system by balancing structural performance, payload capacity, manufacturability, and operational efficiency.

4.3. Results and performance evaluation

The performance of the proposed framework was assessed using the engineering criteria summarized in Table 5.

The comparison in Table 5 is intended to illustrate representative differences in engineering workflow characteristics rather than to establish a direct quantitative benchmark between specific manufacturing technologies.

Table 5 compares a representative conventional tooling-based prototyping approach with the proposed closed-loop engineering methodology. The reported improvements are representative of the investigated case studies and were derived from the cumulative engineering effort associated with geometry acquisition and reconstruction, CAD redesign, additive manufacturing, subsystem integration, and iterative design refinement.

In this study, development effort refers to the total engineering workload required to complete these activities rather than manufacturing time alone. Accordingly, the reported reductions reflect improvements across the entire engineering lifecycle instead of isolated fabrication or assembly operations.

Table 5

Representative comparison between conventional tooling-based prototyping and the proposed closed-loop engineering approach.

Criterion	Conventional tooling-based approach	Proposed closed-loop framework
Design flexibility	Fixed after tooling	Continuously editable CAD model
Manufacturing process	Injection moulding / composite moulding	FDM additive manufacturing
Tooling	Dedicated moulds required	No dedicated tooling
Design modification	New mould or tooling revision	Direct CAD modification
Prototype fabrication	Limited flexibility	Rapid on-demand fabrication
Component replacement	Replacement of commercial part	Local fabrication of individual components
Design iteration	Time-consuming	Feedback-driven
Platform customization	Limited	High
Design refinement	Limited	Continuous

This definition was intentionally adopted because the proposed framework integrates multiple engineering activities beyond manufacturing, including reverse engineering, digital optimization, subsystem integration, and experimental validation.

4.3.1. Development efficiency

Based on the comparative assessment of the engineering activities performed during the development of both validation platforms, the proposed methodology was estimated to reduce the overall prototype development effort by approximately 30–50% and the component-level redesign activity by approximately 35–40% relative to conventional sequential engineering workflows. The reported ranges represent engineering workflow estimates rather than controlled time-based measurements. Overall prototype development effort includes geometry acquisition and reconstruction, CAD modelling and modification, additive manufacturing preparation, subsystem integration, experimental testing, and iterative refinement, and therefore should not be interpreted as manufacturing time alone. The reported reduction ranges were derived retrospectively from the documented engineering activities and represent workflow-level engineering estimates rather than prospectively recorded time measurements (Table 6).

Absolute baseline and proposed-framework values are not reported because the original development activities were not conducted as a controlled time-tracking experiment. The relative reductions therefore represent retrospective engineering workflow estimates based on the documented development and redesign activities of the two case studies.

A dedicated controlled study is planned to quantify the absolute time and engineering effort associated with individual workflow stages and to compare these values systematically with a conventional sequential development approach.

In the implemented case studies, redesign activities were performed primarily at the component level rather than through complete-platform redevelopment. Representative UAV modifications involved the arms, upper- and lower-cover openings, landing legs, and structural infill,

Table 6

Quantitative and estimated performance summary.

Performance metric	Reported value	Evaluation basis
Overall prototype development effort	30–50% estimated reduction	Comparative engineering workflow assessment
Component-level redesign activity	35–40% estimated reduction	Comparative assessment of component-level CAD redesign and modification activities
Maximum geometric deviation (selected UAV components)	0.5–1.5 mm	ICP-based point cloud-to-CAD surface comparison

whereas buoy modifications included the upper cover, cable-routing openings, the channel and groove geometry of the internal capsule, and overall dimensional refinement.

The reported geometric deviation range of 0.5–1.5 mm represents the maximum absolute deviations observed for selected representative UAV components evaluated through ICP-based point-cloud-to-CAD surface comparison in CloudCompare v2.13.2. Accordingly, this range should be interpreted as a representative component-level result for the investigated UAV case study rather than as a tolerance range established for all reconstructed UAV components. The observed deviations were considered adequate for the rapid-prototyping and engineering-redesign objectives of the present study.

4.3.2. Functional validation

Flight experiments confirmed stable operation of the redesigned UAV platform while preserving structural performance and subsystem operation. The coastal monitoring platform successfully integrated environmental sensing, communication, and power-management subsystems and maintained structural integrity during waterproofing and wave simulation tests. Together, the two case studies demonstrate the applicability of the proposed methodology to both reverse- and forward-engineering scenarios under the investigated conditions.

5. Limitations

Despite the demonstrated advantages, several limitations should be acknowledged. The quality of the reconstructed models depends on the accuracy of the initial 3D scanning and point cloud processing, while the performance of FDM-manufactured components remains influenced by material properties and manufacturing conditions, particularly in demanding maritime environments. Furthermore, implementation of the proposed methodology requires access to high-resolution scanning equipment, professional CAD software, and additive manufacturing systems. Although the framework was validated using two representative engineering platforms, additional studies involving larger autonomous maritime systems and long-term deployments are required to further assess its scalability and industrial applicability.

6. Discussion

The results demonstrate that the proposed closed-loop engineering framework enables integration of reverse engineering, digital optimization, additive manufacturing, subsystem integration, and experimental validation within a unified iterative workflow. Unlike conventional engineering approaches, the methodology supports continuous refinement through feedback between digital models and physical prototypes, reducing engineering effort during prototype modification and redesign.

The proposed methodology builds upon recent digital twin and closed-loop manufacturing approaches by extending feedback from manufacturing-level optimization to the complete engineering lifecycle.

The two validation platforms demonstrate that the proposed framework is applicable to both reverse-engineering and forward-engineering scenarios. While the UAV case study highlights rapid reconstruction and structural customization of an existing platform, the modular coastal monitoring system demonstrates that the same engineering principles can be applied to the development of a new maritime platform. These results suggest the potential transferability of the methodology to a broader class of cyber-physical engineering systems.

Compared with conventional production methods based on injection moulding or composite tooling, additive manufacturing enables direct implementation of CAD modifications and localized fabrication of replacement components, thereby supporting rapid engineering iteration.

Overall, the presented case studies indicate that integrating reverse engineering, digital optimization, additive manufacturing, and

experimental validation within a unified workflow can improve prototype-development efficiency relative to conventional sequential engineering approaches.

Unlike previous closed-loop manufacturing approaches, the proposed framework shifts the feedback mechanism from process-level optimization toward lifecycle-level engineering optimization, where reverse engineering, digital redesign, additive manufacturing, subsystem integration, and experimental validation continuously interact within a single iterative engineering process.

7. Conclusion

This study presents a closed-loop engineering methodology integrating 3D scanning, reverse engineering, digital optimization, additive manufacturing, subsystem integration, and experimental validation into a unified iterative development process for unmanned maritime systems.

Validation through two complementary case studies demonstrated the applicability of the framework to rapid prototype development, subsystem integration, and iterative design refinement.

The principal contribution of this work is the formalization of a methodology integrating the complete engineering lifecycle within a unified feedback-driven process applicable to both reverse- and forward-engineering scenarios.

Future work will include controlled quantitative assessment of development time and engineering effort across individual workflow stages, as well as detailed component-level geometric validation of reconstructed and additively manufactured parts using point-cloud-to-CAD comparison. Further research will investigate AI-assisted optimization, uncertainty-aware engineering models, and validation on larger autonomous maritime platforms.

The proposed framework may also be extended to autonomous surface vehicles, underwater robotic systems, and distributed maritime cyber-physical platforms.

CRediT authorship contribution statement

Iliyan Yordanov Iliev: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Miroslav Yordanov Tsvetkov:** Formal analysis, Data curation. **Ramil Akhundov:** Formal analysis, Data curation. **Islam Islamov:** Formal analysis, Conceptualization. **Yordan Atanasov Sivkov:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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