



Testing & Evaluation Report:

Grasshopper: Cost-effective Robotics for Large-Scale Ocean Restoration

Grasshopper testing and evaluation: A seagrass planting robot for coastal restoration

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Introduction

Many organizations globally are researching and administering seagrass planting and related restoration projects. Seagrass restoration has been shown to improve coastal ecosystems and the vital services they provide (e.g. Orth et al. 2020). These have typically relied on human planting, often using scuba divers, which limits planting rates and the scale of restoration achievable, despite evidence that large-scale planting is critical to restoration success (van Katwijk et al. 2016). The Grasshopper system, developed by Reefgen Inc., is a next-generation autonomous system for large-scale, cost-effective marine habitat restoration. These systems combine a robotic platform, machine vision, and precision planting technology, that enables solutions for seagrass and coral restoration that are more scalable than human replanting.

As part of the Synchro program testing and evaluation research work, the team used a 40-foot deep indoor saltwater test tank (located at the Monterey Bay Aquarium Research Institute in Moss Landing, CA) for initial testing prior to later field activities. This work advanced the development of the control systems, vehicle autonomy, and power systems. The large, controlled testing environment enabled rapid iteration and refinement of the robot's system navigation, allowing the team to deploy critical infrastructure for precise motion and localization testing. These developments are essential steps toward unlocking full system autonomy and enabling scalable, efficient nearshore marine restoration operations. The key testing hypotheses evaluated here are 1) Does visual-inertial odometry provide localization and navigation data sufficient to guide planting? And, 2) Does the vehicle's thrust control yield sufficient navigation control and stability to function in synchrony with the visual control systems?

As the current testing phase concludes, the partnership with Synchro has proven to be a valuable support to Reefgen's development efforts. Access to local, high-quality testing resources has been key to accelerating progress and validating new system capabilities of operating systems for all of the autonomous vehicles.

Looking ahead, Reefgen aims to expand testing in natural marine environments to further advance system autonomy, reduce the need for human intervention, and support scalable, resilient reef restoration efforts.

About the Robots

Reefgen is developing three types of specialized underwater vehicles:

- Shoot Planting Robot (Figure 1)
- Seed Planting Robot
- Coral Planting Robot



Figure 1. Grasshopper seagrass shoot planting robot doing a restoration activity in the Puget Sound, WA spring 2025.

While each system is tailored to its specific restoration task, the planting platforms share several core components and technologies, enabling modularity and streamlined development across applications.

The planting systems are structured around three core components: the Topside Control Station, the Vehicle, and the Planter Payload, all integrated through a modular software architecture.

Equipped with cameras for operator oversight and machine vision for site localization, the vehicles also include onboard sensors to monitor system health. Their power systems use

onboard batteries with management capabilities and can connect to surface-supplied power to extend operational endurance. Key features include miniature servo motors with feedback capabilities that support planting activities and autonomous motion control across various marine environments.

During the Synchro testing days, Reefgen used the Shoot Planting Robot as the core vehicle for autonomy development, validating motion control and navigation systems in a controlled environment. These efforts are critical steps toward unlocking full autonomy, enabling scalable, efficient restoration of nearshore ecosystems at speeds that match or exceed traditional planting rates.

Activities and Outcomes

Testing focused on validating several developments that are important to Reefgen's autonomous planting systems. These included both testing new features and confirming improvements to previously tested components. The controlled environment provided by the test tank allowed the team to confirm functionality, identify areas for refinement, and gather valuable data. The following results reflect the progress made during this testing phase and the foundation it sets for continued field deployment.

Fiducial-Aided Localization

A localization system was built by Reefgen to inform vehicle position relative to the reef environment by using multiple sensors. This system allows the vehicles to navigate more accurately and autonomously based on their estimated location.

The evaluation used the open-source Robot Operating System 2 (ROS 2, <https://github.com/ros2>) and a localization framework that combines data from visual sensors with information from onboard sensors. This combined data is transformed into a format that the vehicle can use for stable positioning and navigation. The main source of global position data is visual-inertial odometry (VIO) using the Luxonis OAK-D camera. To improve positional accuracy, the system was augmented with AprilTags, visual markers that the robot can detect to determine its exact position and orientation. These tags serve two purposes:

1. They provide fixed reference points to verify and validate other localization methods during testing.
2. In deployment, placing these tags at known locations in the underwater environment allows the robot to correct its position, improving accuracy in challenging conditions.

While visual markers were not used during testing in the MBARI test tank, measurable improvements in the robot's localization performance from prior effort were still observed. This provided key feedback on the system performance and its potential to perform even without external reference markers.

New Control Modes

A flexible control system was created by adopting an open-source thruster manager. Instead of relying on hard-coded positions, this system automatically allocates thruster forces based on the robot's shape, allowing for improved stability and easily adjusting control settings. For example, a vehicle's orientation can now be locked to keep camera images stable during reef mapping. Individual controllers were developed for different motion directions, which can be activated separately or combined as needed, giving the team much greater control in dynamic reef environments.

This new control pipeline was successfully tested in the test tank, including implementation and testing of depth (z) hold and yaw rate stabilization (Figure 2). This new pipeline was then tested in a real-world setting during a seagrass deployment in Wales. The control system helped the vehicle to maintain a steady speed and heading while moving between the boat and the planting site. As a result, the moving time was reduced by half or more.

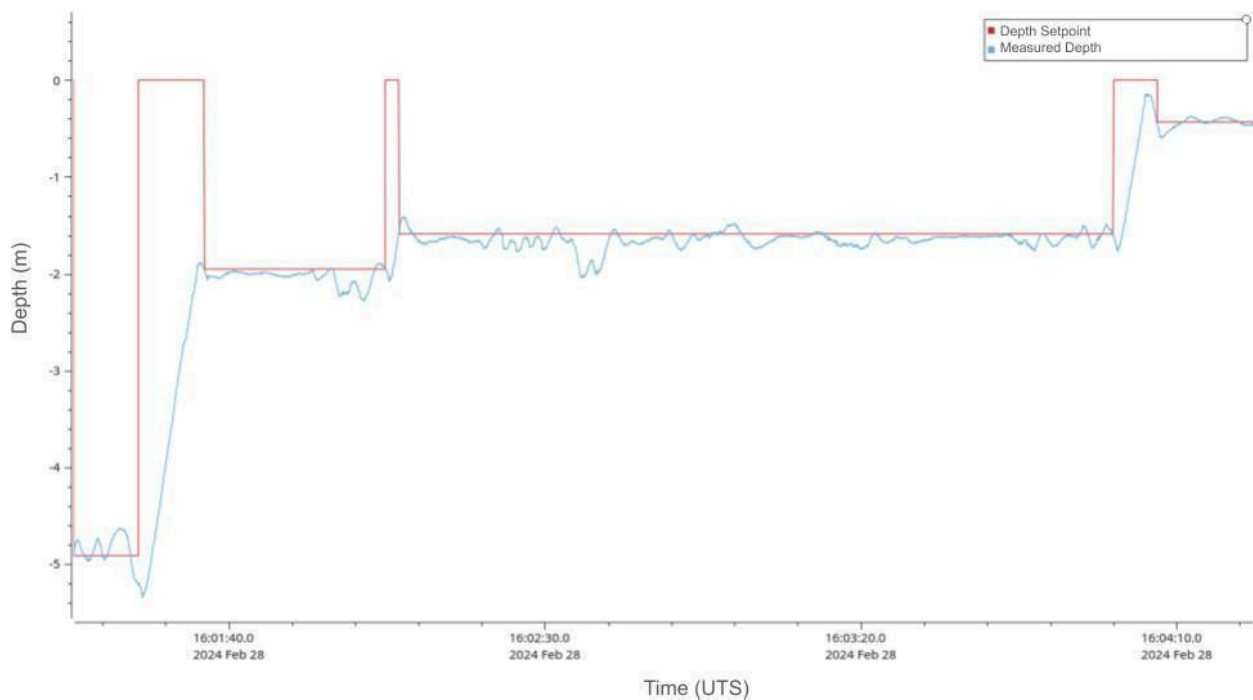


Figure 2: Depth position of the vehicle during a test in the MBARI test tank. As shown, the vehicle is able to stabilize around multiple depth set points, minimizing perturbations created by surge and sway motions as it moves through the water.



Figure 3: The team during controls testing at the MBARI test tank. The robot, visible on screen, is following a transect line across the bottom of the tank, testing the yaw stabilization and measuring the cycle rate of the planting payload.

To continue this work, a controller for three degrees of freedom attitude (roll, pitch, and yaw), as well as surge (X) and sway (Y) position, is under development (Figure 4-6). This controller will leverage Reefgen's localization work and TF transforms to enable point to point navigation on reef environments. Reefgen has begun testing this controller in simulation to assess controller performance in the presence of waves.

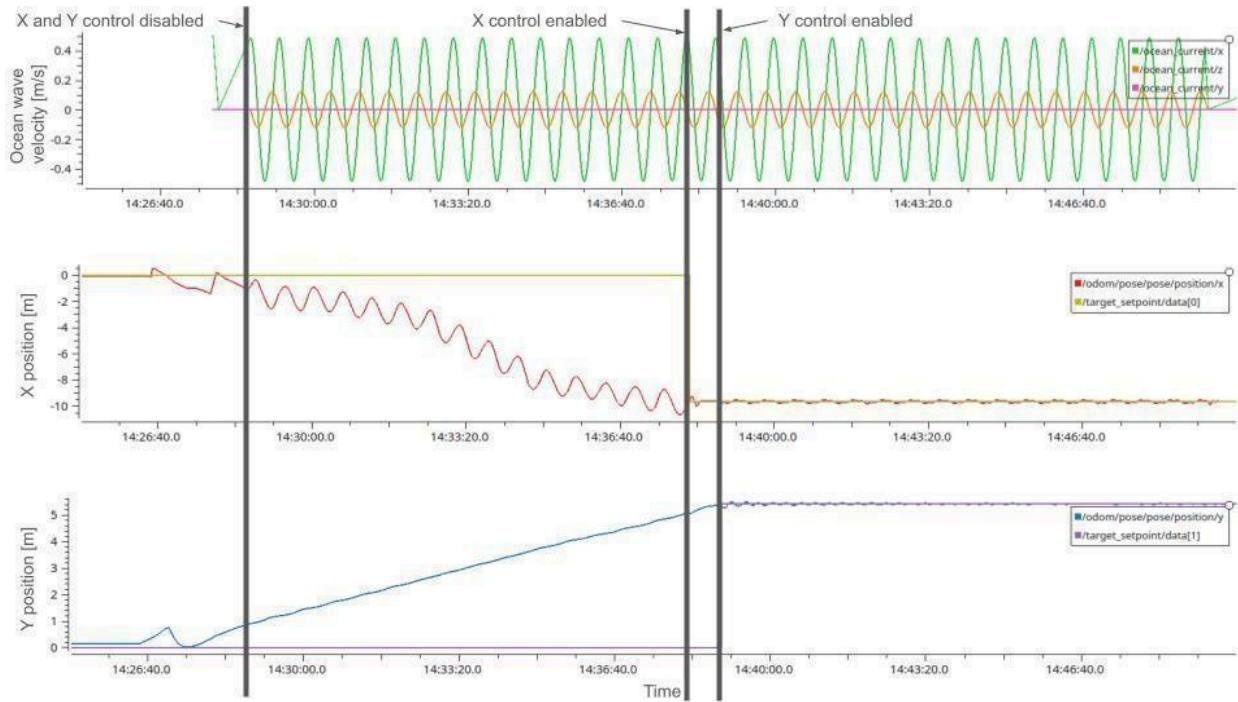


Figure 4: [Top] wave velocity profile, for a simulated wave traveling in the surge (X) direction. [Middle] X position of the vehicle over time. [Bottom] Sway (Y) position of the vehicle over time. At the 1st vertical line indicator, wave action was enabled while the vehicle was in depth hold and attitude stabilization mode. The vehicle drifts in x and y position over time. The 2nd and 3rd vertical line indicators are when x and y controls were enabled respectively. The vehicle then holds at its set position with minimal oscillations.

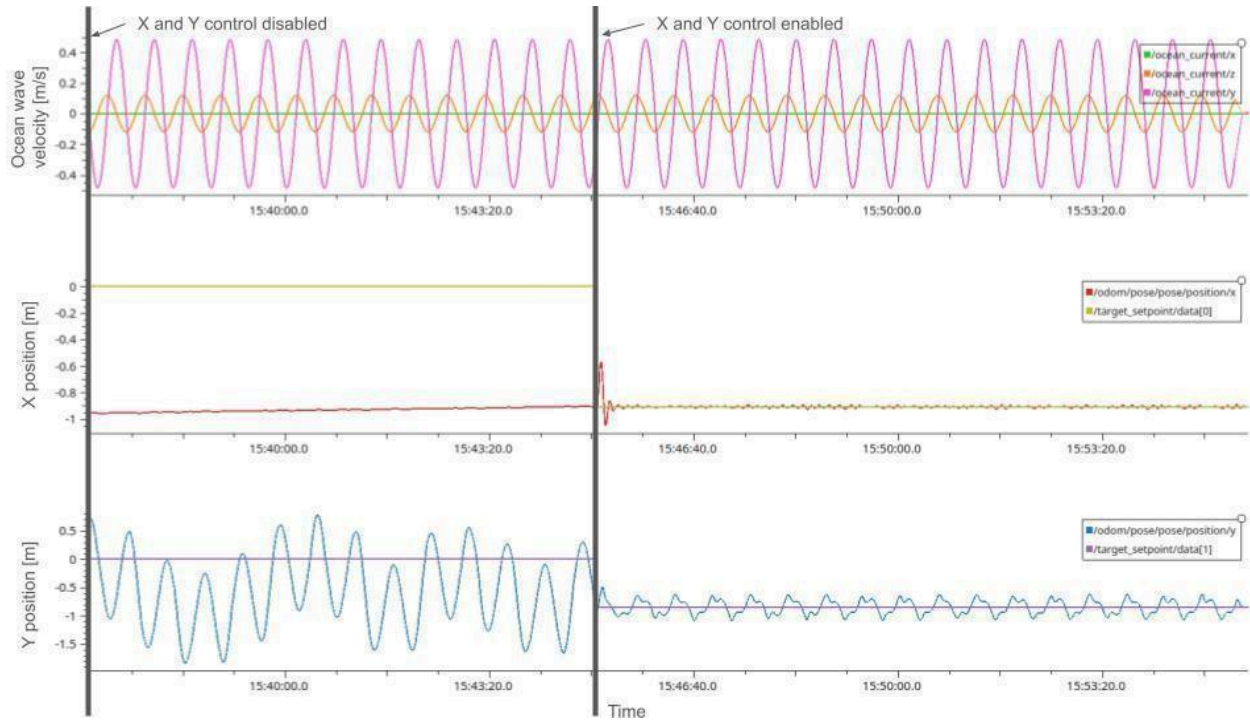


Figure 5: [Top] wave velocity profile, for a simulated wave traveling in the sway (Y) direction. [Middle] X position of the vehicle over time. [Bottom] Y position of the vehicle over time. At the 1st vertical line indicator, wave action was enabled while the vehicle was in depth hold and attitude stabilization mode. The vehicle drifts in x and y position over time. The 2nd vertical line indicator is when x and y controls were enabled. The vehicle then holds around its x and y position, however the y position oscillates more than when in the presence of a wave moving in the x-direction.

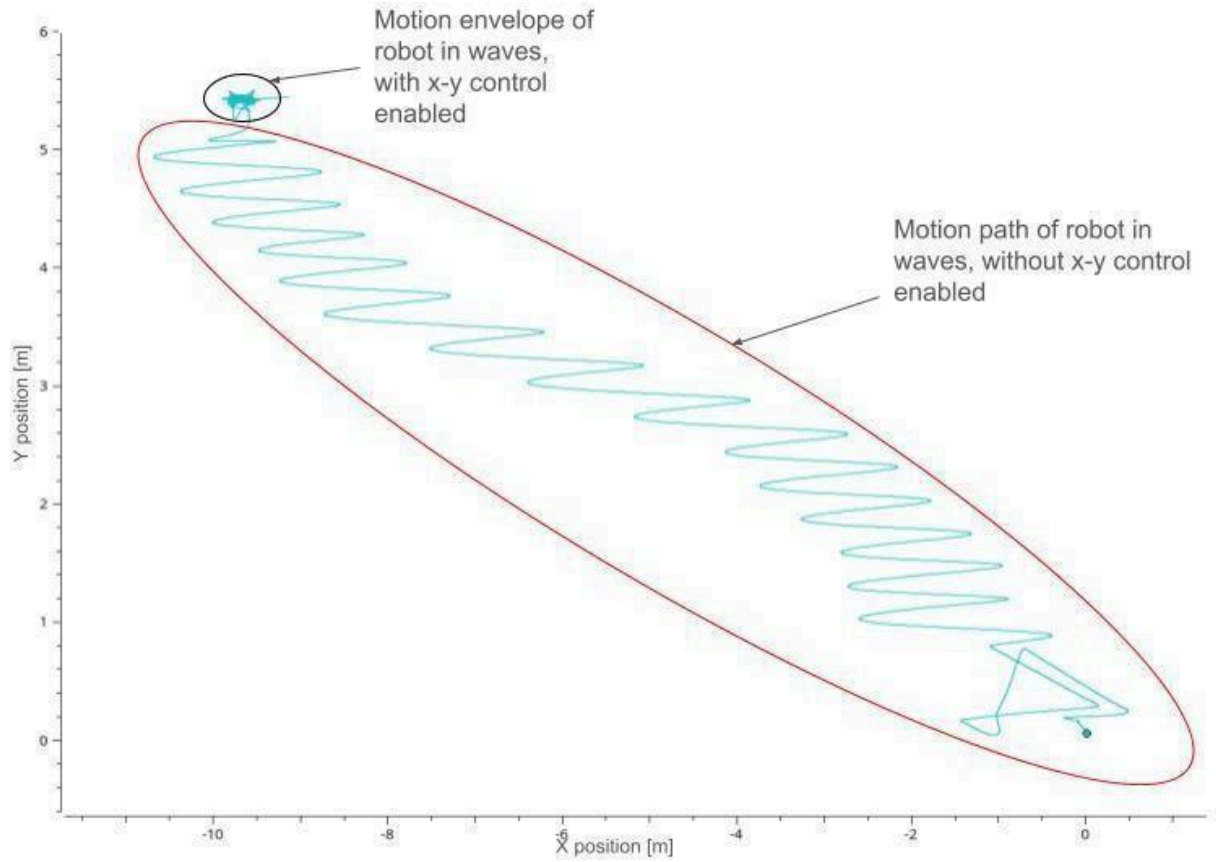


Figure 6: Position of the robot over time in the x-y plane while an x-direction wave was applied. The oval in red outlines the path the robot took while the x and y controllers were disabled. The black oval outlines the path the robot took while the x and y controllers were enabled.

Partnerships

In relation to work in an indoor saltwater test tank in Moss Landing, Reefgen established a connection and partnership with Moss Landing Boat Works, who offered access to their facilities for setting up a seagrass nursery and provided opportunities for real-world testing in natural marine conditions.

This partnership has expanded testing capabilities for Grasshopper beyond the lab, allowing Reefgen to operate within a designated 0.1-square-mile area inside the Moss Landing breakwater. This site provides a diverse range of nearshore marine conditions, offering an ideal environment to further test, validate, and refine the autonomous planting systems under realistic field conditions.

Engineering with Impact

The findings and data included in this report may be of interest to a wide range of stakeholders involved in marine conservation, coastal infrastructure, and climate resilience. This could include port and harbor managers, who are increasingly exploring nature-based solutions to mitigate erosion. Coastal resilience planners and municipal environmental departments could be interested, as they are tasked with designing adaptive strategies for shoreline protection. Lastly, marine spatial planners and restoration practitioners working to integrate autonomous technologies into seagrass and coral recovery efforts may also find value in these findings. In addition, research institutions and policy-makers focused on scaling restoration and blue carbon strategies may find the system-level insights and field data valuable to evaluate the feasibility of robotic restoration at scale.

End User Perspectives

Feedback was gathered from several potential end users with expertise in seagrass restoration, marine technology, and coastal resource management, including one reviewer with direct field experience with the Grasshopper system during 2024 deployments. Across respondents, there was broad recognition of the system's potential to transform large-scale restoration efforts. Precise seed injection into sediment, rather than broadcasting, was identified as a key advantage, with the potential to significantly improve seedling establishment success rates and to substantially reduce field operation time as system speed and reliability improve. Beyond current testing conditions, promising applications include deeper-water environments where diver-based methods become less practical, as well as large-scale restorations where reduced diver burden during planting could improve restoration efficiency and minimize impacts to existing beds. Additionally, the three current platforms, designed for seagrass shoot planting, seed planting, and coral restoration, may present an opportunity for consolidation into a single modular vehicle with interchangeable tools, reducing development complexity and long-term costs.

Feedback also highlighted the information needed to support broad adoption. Direct comparisons to conventional diver-based methods, including transplant rates, shoot survival, and cost breakdowns at varying deployment scales, were identified as priorities, as was situating the Grasshopper within the full restoration workflow and acknowledging how this differs from existing restoration protocols (e.g. harvesting donor material and replanting). Questions around market readiness were also raised, with recommendations for deeper investment in customer discovery, competitive analysis, and field testing across diverse geographic and thermal environments. This feedback reflects strong interest in the technology and underscores the value of continued field testing, transparent performance reporting, and sustained engagement with restoration practitioners and resource managers as the system advances toward broader deployment.

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Acknowledgements

The authors appreciate financial support from the National Science Foundation, Schmidt Marine Technology Partners, and Impact Assets.

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