# An Easy-to-Use, Online, Visual-Inertial, EKF-SLAM System for AUV Localization

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***Abstract*—In this work, we introduce a general and easy-to-use software library for real-time, robust, fiducial-assisted, Extended Kalman Filtering (EKF) for Simultaneous Localization and Mapping (SLAM) on AUVs within feature-sparse environments.**

## I. Background

Current work in autonomous underwater vehicle (AUV) control is heavily focused on applying control techniques first developed for land and air robots. These methods typically require accurate localization of the robot body, but AUVs present additional challenges not found in land and air robots. First, AUVs suffer from a lack of absolute inertial-frame reference measurements, such as those from GPS sensors. To rely purely on dead-reckoning methods such as ring-laser gyroscopes and Doppler Velocity Logs (DVLs), an AUV's sensors need to be highly accurate - and therefore costly and large - to minimize the accumulated drift to a manageable level. Additionally, AUVs operate in feature-sparse environments, such as open water or testing tanks. Therefore, existing visual-SLAM libraries such as ORB-SLAM2 [1] or UcoSLAM [2] cannot be simply adapted for AUV use. Finally, sonar technologies can provide underwater landmarks for use in SLAM, but are restricted to deep, large, and clutter-free environments.

## II. Prior Work

Increasingly, research has been conducted in utilizing fiducials such as Apriltags [3] to provide both inertial-frame pose measurements and easily detectable features for general robotics use. Both graph-based [4] [5] [6] and filter-based [7] [8] [9] [10] localization algorithms have been used to incorporate fiducial measurements for localization purposes.

Fiducial-assisted localization has been applied to both general robotics use in GPS-deprived environments, as well as specifically to AUVs. On land, [9] presented a general Apriltag EKF-SLAM framework as an affordable motion-capture system. [7] applied a simpler fiducial-assisted EKF for localizing quadcopters in indoor spaces to aid in construction. Both works demonstrated fiducial-assistance's capability to drastically improve localization performance in GPS-deprived settings. Underwater, fiducial-assisted localization has seen similar success. On the proof-of-concept end, [4] and [10] both demonstrated fiducial-SLAM's viability for localizing a large AUV within a testing tank. Perhaps most striking, however, is the work by Duecker et al. [8] in applying a fiducial-assisted localization-only EKF to localizing micro-AUVs in real time to perform high speed hydrobatics maneuvers. See Figure 1. for an illustration of how fiducials have been used in prior works.

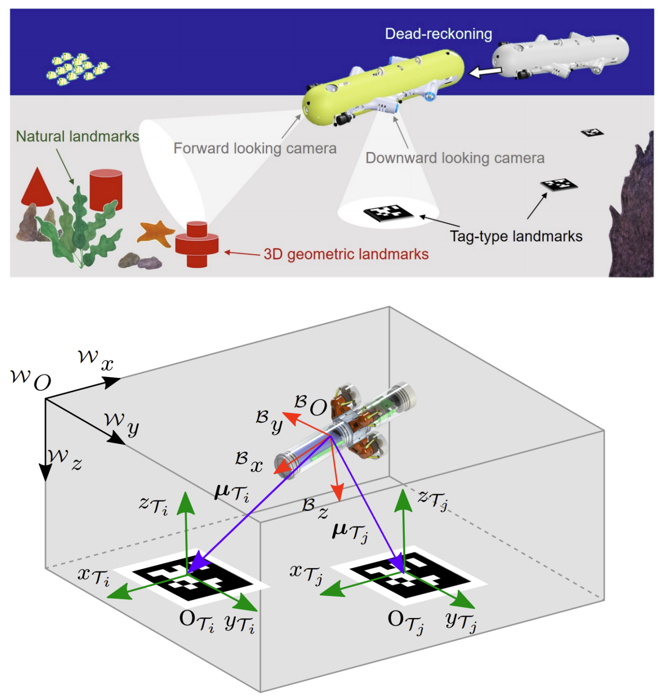


Figure 1. Illustrations of how AUVs can utilize fiducials for localization. Jung et al. [10] and Duecker et al. [8]

In all works, fiducial-assistance demonstrated significant performance improvements over pure dead-reckoning methods. However, all prior works in fiducial-assisted localization for AUVs have been lacking in three areas: speed, scalability, and robustness. In terms of speed, only Duecker et al. [8] performed their localization in real time. For scalability, past works have often required precise placement and measurement of fiducial maps a priori. Finally, past EKF implementations have each had their own performance and robustness inefficiencies that can each be improved upon (further elaborated upon below). The combination of these factors means that there is still a need for a tool that provides real-time, robust, and plug-and-play fiducial-assisted AUV localization.

## III. Contribution

In this work, we introduce a general and easy-to-use software library for real-time, robust, fiducial-assisted, EKF-SLAM on AUVs within feature-sparse environments. Deployment is made easy through the use of standard ROS tools, and no prior mapping of fiducials is needed for localization. Our implementation can be seen as an extension of [8], but combined with many performance and ease-of-use improvements. These improvements can be broken down into three major areas:

First, we speed up the existing solutions by using a GPU-accelerated Apriltag detector on a Jetson Nano. This way, we are able to detect Apriltags at 600% the rate of [8], on a single board computer only 10% larger than the Raspberry Pi 4 used in their work.

Second, besides just localization, we also implement mapping of the fiducial landmarks. Duecker et al. [8] and Kayhani et al. [7] used an EKF and fiducials to localize the robot, but did not estimate and update the fiducial poses online. Instead, like [9], we perform EKF-SLAM by including the fiducial poses into our state vector. This way, an a priori fiducial map is no longer needed, and if one were to provide a priori measurements, any inaccuracies would be corrected for.

Finally, we incorporate numerous general EKF implementation improvements. First, as with [9], we not only estimate the poses of the body and tags, but also the IMU biases and camera-body extrinsics. Next, we implement a Runge-Kutta discretization for the nonlinear process model in our Predict step, as opposed to the simple Euler-discretization implemented in all prior works. Finally, similarly to [9], when calculating our Innovation term we directly use the pixel coordinates of the tag corners', as opposed to their pose in Euclidean space. Through these improvements our EKF-SLAM implementation has significantly less drift over long missions, and is also more robust to periods without detections.

## References


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