Autonomous Takeoff & Landing of Small UAS from the USV

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***Abstract*—A successful combination of the Interoperable Heterogeneous Unmanned Autonmous Systems for future missions at sea is becoming a reality. An Unmanned Surface Vehicle (USV), as the central node and main transport mechanism, can be used to carry Unmanned Aerial System (UAS) and Unmanned Underwater Vehicles (UUVs) to distances over several hundred miles. The system is designed to be modular and can easily be scaled up if needed. In this paper, the initial implementation of an advanced UAS takeoff/landing from/to a 16 foot catamaran USV (70x40 inch landing area) provides solutions that can enable the interoperability, coordination and cooperation of autonomous mobile marine robots in GPS-denied environment are presented. To enable such a heterogeneous network three main research areas have been blended: 1) image processing, 2) state estimation, and 3) cooperative control and autonomy. This paper focuses on the first two components and addresses the integration of the third one. Due to the challenges of the maritime environment, novel software and hardware have to be investigated to provide the level of flexibility and features that are required for efficient and robust landing. Robust and reliable communications have to be developed and implemented to enable an efficient sharing of data and control messages among heterogeneous surface and aerial platforms.**

I. Introduction

Until recent developments made in technology, the combination of USVs, UASs, and UUVs had only been visions for the future. A similar concept in ocean exploration was introduced with Autonomous Ocean Sampling Network (AOSN) two decades ago [1]. Various research groups around the world are pushing forward on the technology needed for successful implementation of this vision of multivehicle autonomy and heterogeneous robot operations. The unique approach presented in this paper is that the interoperability in both hardware and software significantly reduces the manning requirements for deployment of such systems.

The objective of the Center for Innovative Naval Technologies - Information Dominance (CINT-ID) program's Heterogeneous Autonomous Mobile Maritime Expeditionary Robots (HAMMER) project is to operationally integrate platform agnostic unmanned surface, aerial, and underwater vehicles in order to perform cooperative missions. HAMMER system consists of the multiple maritime robots. A basic configuration is one unmanned surface craft that carries, deploys, recharges, and recovers an aerial and underwater robot; see Figure 1.

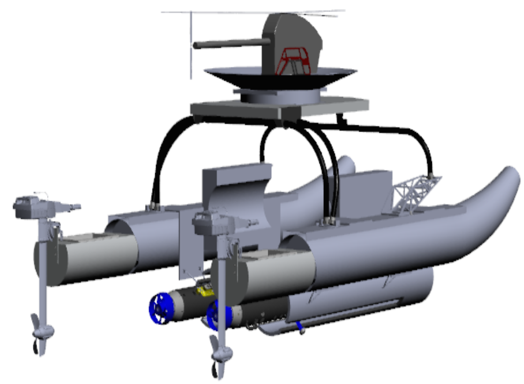

Figure 1: HAMMER basic triple

This is a basic triple but any combination is possible and the system is scalable. We also consider multiples of the HAMMER system that are working in conjunction with other manned and unmanned Navy assets. SSC PAC is focused on the cooperative integration of unmanned systems in the maritime domain. Current research efforts are focused on core flight tasks for UAS, specifically autonomous takeoff from and landing on an unmanned surface vehicle (USV) while in motion. This is a critical maritime UAS capability. Without such abilities maritime UAS will be limited in range and flight time, and will require other measures for landing or retrieval, thus limiting their mission profiles and operational usefulness. To accomplish this complex task SSC PAC is developing, testing, and verifying a suitable sensor suite and flight algorithms for the Vapor 55 UAS, built by Pulse Aerospace and modified by the Unmanned Maritime Vehicle Laboratory of SSC PAC.

A similar system for performance comparison, previously used on naval ships, is the QH-50 Drone Anti-Submarine Helicopter (DASH) Program. The DASH system was used by the Navy to gather over-the-horizon target data to the destroyer's five-inch batteries, and used a transponder for better radar tracking. This system quickly diminished in use. The lack of a feedback loop from the drone to the controller, and its low radar signature and lack of transponder, accounted for 80 percent of all drone losses. This drone's failure led directly to billions of dollars invested in manned aircraft first, in the Lightweight Airborne Multi-Purpose System (LAMPS), followed by the MH-60R and M-60-S aircraft systems.

State-of-the-art Helicopter Autonomous Landing System (HALS) by Sierra Nevada Corporation uses a 3D image-rendering 94 GHz pulsed millimeter wave radar (provides a real-time picture of the landing zone on two cockpit displays), global positioning system (GPS), inertial sensors, and cockpit displays to enable takeoff/enroute/landing in all Degraded Visual Environment (DVE) conditions [7].

Cooperation of multiple vehicles has received increasing attention as group performance often leads to higher efficiency and robustness. It is an interesting research topic because it leads the exploration of the differences between a group of robots vs. single robot behavior. Cooperative autonomy between UAS and USV heterogeneous systems has many interesting applications. One example is a riverine environment where USV can only sense a certain distance as a river curves. UAS can be the "forward eyes" of the USV that can generate a trajectory for the USV. This, together with sensors onboard of the USV, can enable the system to work in a GPS-denied environment. In [3] the cooperation and coordination of different underwater assets has been addressed. More specifically, the authors present a mission to precisely guide an inexpensive underwater vehicle to an underwater target using the navigation suite and control system of a more capable underwater vehicle. In order to cooperate, however, devices have to communicate and share information.

With the propulsion, power management and transfer, and sensor systems of the USV, the landing and takeoff algorithms of the UAS, the future integration of a UUV, and overarching communications framework, the HAMMER project is soon to achieve heterogeneous system autonomy. Several sub-systems working together as one will minimize operator requirements and reduce the manpower necessary for system success. Our goals with the HAMMER system encompass that – getting 80 percent of the way there without waiting the decade(s) it would take to reach 99 percent of the proposed capabilities.

The rest of the paper is organized as follows:

Section II describes our general approach for autonomous takeoff & landing, hardware and software needed for it on both the USV and the UAS side. The image processing software is presented in Section III, also describing the integration with the stereo camera and LIDAR-Light Detection And Ranging sensors. Section IV explains our estimation scheme and path planning algorithm. The experimental activities are detailed in Section V. Finally, Section VI concludes the paper.

II. Approach

Operating a UAS from a USV at sea will require sophisticated flight operations and the development of new algorithms based on flight techniques used by Navy/Marine Corps helicopter pilots, such as a stern approach while both the aircraft and ship are heading into the wind. Evaluation of these techniques will allow for the analysis and development of UAS-specific flight states and parameters to create stable flight patterns. Algorithms are being developed to maneuver both the UAS and USV into the correct orientation based on the angle and distance between the two platforms, which will be especially challenging when both platforms are operating autonomously.

A. Takeoff

Autonomous UAS launchs from a USV require data from onboard sensors to inform the UAS of the sea and air state, which can impose limitations on the UAS's takeoff capabilities. Limits on wind speed and direction, sea state, and USV speed are just a few of environmental factors that can limit when and how the UAS can take off. Once the data collected deems it suitable to fly, the UAS can start its motors with a downward force to minimize any lateral movement that might occur during unlatching. Since data has been collected on air and sea state, a trajectory can be planned and a controller can track that trajectory accurately. The force of the rotors can immediately be used to provide an upward force, and the trajectory tracking can be followed. Stabilization can occur during and at the end of the takeoff, giving some predefined values for height, distance, and/or speed the UAS must reach before takeoff is considered complete. This stabilization will take into account any issues the UAS had in its trajectory tracking.

B. Landing

Autonomous UAS landing on a USV requires the sophisticated integration of: 1) GPS location, range, and height calculations, 2) detection and tracking of the USV and landing platform, 3) fusion of an Inertial Measurement Unit (IMU) and camera data from the UAS and USV, and 4) flight path planning to define an optimal path for the landing descent. The algorithms are focused on efficiency and responsiveness and are split up into different stages. Landing was the first focus, since it proposed a more challenging problem that could also

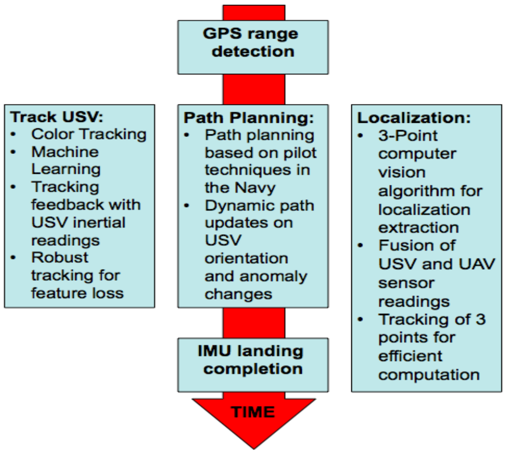

Figure 2: Landing Algorithm in the time-domain. Each task runs mostly in parallel with all other tasks. Each does its own job, but sensor fusion and parallelism is necessary for an accurate landing.

give insight into takeoff and other behaviors tied with the USV. First, the UAS and the USV must get within range of each other using their GPS coordinates. For this phase of landing we will initially explore the use of the existing platform GPS units. In the future, recently acquired Piksi RTK GPS units from Swift Navigation can achieve 2-3 cm accuracy in relative distance between the UAS and USV if the GPS signal is stable.

Once the GPS coordinate of the USV has been tracked and the UAS is in that 30 meter range, detection and tracking of the UAS is performed with the aid of other sensors other than GPS. This is a combination of search behaviors and computer vision techniques for anomaly and 3D model detection. A flight controller focuses on moving closer by enlarging the model in the camera's image until the next step can be performed. This next step utilizes the three-point algorithm described in [2] to use a single camera to perform depth calculations. In our implementation, some adaptations are made: the three points are required to be orthogonal and aligned with the USV body axes, and all three points are on the same plane. These three points create two vectors representing the forward and right vectors of the USV, and a simple cross-product can be used to find the up vector. Geometric references of the three points and the orientation of the USV can now determine the position of the USV as well, and changes in these values between frames can determine the movement of the USV in rotational and linear dimensions. Therefore the full state of the USV can be determined, from the use of a single camera on the UAS. We do not exclude that the next payload module for the UAS will include the stereo camera pair which can most likely improve the distance to the USV measurement. The stereo camera algorithms are described in Section III.

The HAMMER system is much more robust than this however. The total state of both the USV and the UAS can be determined by a few systems: the IMU of the UAS, the IMU of the USV, the sensors (stereo camera and LIDAR) on the USV, and the camera/sensor system on the UAS. When the IMU and sensor information is paired and fused in world space, the system can create an encompassing mosaic of the two system's states and an accurate representation can be created for a precise landing. During this whole process, a path is planned by the UAS to land on the platform in a way that resembles certain parameters. These parameters come from techniques used by the Navy pilots, as well as the state that the UAS needs to achieve to meet the Navy techniques. Navy pilots land by coming over the aft of a ship, while the ship and the aerial system are both heading into the wind. Issues arise when the USV is spotted and the three-point algorithm cannot be performed due to the angle or distance of the USV. The UAS still needs to make its way into the wind coming over the aft of the USV, while also enabling the three-point algorithm to begin at an appropriate distance. This requires some sophisticated intelligence in the UAS autonomy for path planning and computer vision. The flight controller will focus, at first, on enlarging the 3D model in the camera's image. It also needs to find the three points on the landing platform in order to track the USV's state information accurately. Therefore, the UAS needs to determine the general direction to face and the general position relative to the USV to maintain those three points. Though coming in from above should alleviate this issue almost entirely (due to the USV's suspension dampening any major rotations of the landing platform), some identification of 3D points of interest on the USV's model can make landing a more robust system. For the landing algorithm summary see Figure 2.

C. Landing station integration

The Vapor 55 UAS and a surrogate UAS landing station built for the Wave Adaptive Modular Vessel (WAM-V) USV, manufactured by Marine Advanced Research, serve as the test platforms for autonomous takeoff and landing. During 2015 a team comprised of San Diego State University students was tasked to design UAS Launch and Recovery System to enable the helicopter to be charging while centered on the platform. A conical shaped landing station was designed to help guide the UAS onto the USV. The UAS can be either tethered or untethered to the USV. The landing station has a spring-loaded mechanism to lock the helicopter in while the surface vehicle is underway. In Figure 3, the modified

Figure 3: Modified (payload module added) UAS locked onto the LIDAR equipped landing station

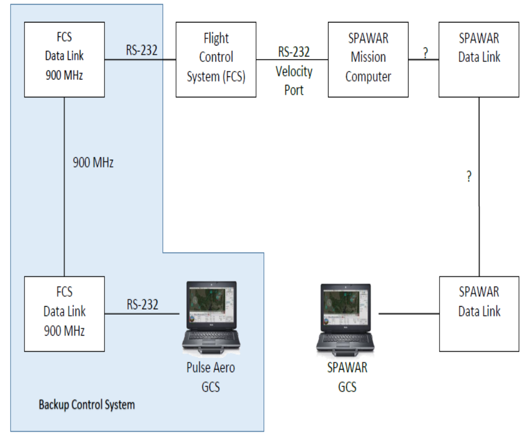

Figure 4: The interface between the UAS and added payload module

(payload module added) UAS locked onto the LIDAR-equipped landing station is shown.

D. Payload Module Addition and Interface with UAS autopilot

Vapor 55 UAS is a robust system with an advanced autopilot. The H-infinity controllers and the helicopter dynamics models to which they stabilize are included. In case of GPS loss, the VAPOR 55 automatically and seamlessly switches to an attitude controller. Smart automatic homing (Data Link Lost Protocol), automatic autorotation feature, automatic RPM setting for various altitudes up to 10,000 ft, and automatic magnetic declination setting are additional advanced features. An additional 10 lbs of payload can be added to the UAS. 45-60 minute endurance (depending if hover or waypoint flight) can be achieved with the payload module, resulting in approximately 15 km of flight from the USV. Wind disturbance up to 35 mph can be compensated for. SSC PAC opted for the interface which allows the designer of additional UAS behaviors to directly provide guidance to the helicopter through velocity and heading rate commands. This port supplies 50 hz of navigation data and a payload computer can respond with 50Hz commands on an RS-232 port. SSC PAC has added an additional 5 GHz datalink to be able to communicate with the payload computer and stream live sensor data. Figure 4 shows the interface between the UAS and added payload module. The payload module contains modular mission planning & guidance and sensor processing software (based on Robotic Operations System and Mission Oriented Operating Suite), BeagleBone Black computer board, parallella computer board, Hokuyo UST-20LX LIDAR, radio router board, Leopard Imaging Video Camera(s), and Ubiquiti XR5 XtremeRange5 radio board and antenna.

III. Image Processing

The operating environment and small payload capacity of the targeted UAS family requires sensors that are lightweight and robust, and unique maritime flight algorithms. Making the assumption that the UAS knows what to look for and that the landing platform dimensions are known enables an initial sensor suite to be developed using optical cameras. As described in Section II-B, a single camera is being used for stereo-like vision to perform vector calculations since distances between points on the landing deck are known. Once an initial capability is proven, various filters and enhanced camera optics can be integrated to enhance UAS performance under wider variations in weather and light conditions. In the future, other sensors like thermal, infrared, LIDAR, and ultraviolet cameras can be integrated and tested.

An IMU and Global Positioning System (GPS) are crucial sensors needed for most robotic platforms. The GPS & IMU allow robots to know their states data such as position, velocities, acceleration, orientation, and angular rates. These data variables must be extracted and published before complex tasks so that navigation and obstacle avoidance can be performed. A LIDAR is another crucial sensor used in mobile robotic platforms that can measure range and bearing to objects surrounding a robot. A pair of video cameras with stereo image processing can obtain the same measurements. Before the image processing procedures can be implemented, image frames must be extracted and logged with their corresponding timestamps which also enables georeferencing of the obtained imagery.

The LIDAR reads depth information by rotating a laser about its horizontal axis and recording the depth of each point by the time spent for the light to travel and return back to the sensor. The LIDAR positioned on the landing platform (see Figure 3) will be used to determine the position of the lowest part of the UAS at the final stage of landing.

A stereo camera integrated on the landing station will be used to detect and track the UAS when it enters the camera field-of-view (FOV) about 30 m from the landing station. It will be used to track the position of a UAS relative to the WAM-V to assist in landing on the USV platform. With the use of a stereo camera and synchronized left and right images, a 3D point cloud can be generated via ROS stereo image proc package. The package is implemented through OpenCV's Block Matching algorithm [9]. The parameters can be optimized to track the UAS. These include the texture threshold and range parameter which are adjusted to remove noise and pronounce the UAS's "blob". A 3D stereo point cloud provides a unique method for image segmentation. Since the 3D data generated is defined to scale, the object's volume and shape can be used for fast segmentation. The data is prepared for this task by first partitioning the point cloud into clusters via the Point Cloud Librarys (PCL) Euclidean Clustering Function function [10]. Since the UAS will be out in the air away from obstacles (not right next to a building, on a wall, or in a tree), the cluster tolerance can be increased such that the number of clusters are reduced from hundreds to single digits. Each cluster's perceived surface area is calculated with smaller and larger clusters being ignored. Clusters which are too long/skinny in either axis are also ignored. The remaining UAS candidate clusters represent good test cases for further 2D object recognition methods.

With image segmentation done by point cloud clustering, each cluster can be projected into the left camera's image via the camera's calibration matrix. Each of the cluster's images is compared against a trained classifier of the UAS. The classifier was implemented by OpenCV's (Lienhart) cascade classifier [11] using local binary pattern (LBP) features with 20 stages. The image must pass all 20 stages before being labeled as the UAS. If the image is indeed the UAS, then the corresponding cluster's 3D center is determined to be the location of the UAS.

Once the UAS has been found, a 3D region of interest (ROI) is applied. This causes the next algorithm iteration to ignore all points outside of the ROI cube. When the copter is not found, the ROI cube's volume increases to compensate for any 3D translations the UAS may have traveled. This technique reduces the processing required to find the UAS and thus increases the success frequency.

IV. State Estimation and Cooperative Control

In Section II-B it was shown that the full state of the USV can be determined just from the use of a single camera on the UAS. In Section III it was shown that the position of the UAS can be determined from the use of a stereo camera on the USV.

Thus, the total state of both the USV and the UAS can be determined by a few systems: the IMU of the UAS, the IMU of the USV, the sensors (stereo camera and LIDAR) on the USV, and the camera/sensor system on the UAS. When the IMU and sensor information is paired and fused in world space, the system can create an encompassing mosaic of the two systems states and an accurate representation can be created for a precise landing.

A. State Estimation

We implemented a standard Extended Kalman Filter (EKF) to propagate the state and incorporate the sensor data. The model of the helicopter, simplified by constraints from the autopilot, was treated as a 2D particle with x- and y-velocity and a heading angle. The z-axis also has an independent 1D linear simple model for the z-velocity.

Through simulation, the controller was tested with a variety of simulated sensor feedback to the filter. For example, low-level sensor data form the IMU-like acceleration and rotational rates. These can be fed into the filter at high rates of 50-100 times a second, while accurate high-level sensor data like position is fed back at a slow rate of 1-3 seconds per reading. The results were successful position drift went from one meter a second (due to integration errors and sensor bias and errors) down to centimeter per second drift. Even though simulations are not perfect representations of the real world, these results show a 100x reduction in inaccuracies for estimating the state of the system.

B. Path Following and Cooperative Control

For path planning the landing of the UAS on the USV, we took an iterative approach to the problem, recognizing that both vehicles must be moving when landing in order to make the platform more stable and easier to land on. Once the vehicles are within range of each other (30-50m), the path planning begins. Using the heading of the UAS as the starting vector and the heading of the USV as the ending vector, the algorithm constructs a Bezier Curve to connect the two vectors. This is used for continuity along positional, velocity, and acceleration constraints, as well as continuity with the starting and ending vectors. The algorithm for planning how the UAS follows the path is as follows:

- The Bezier Curve is generated based on a small set of rules that controls the curvature of the spline, making sure the UAS can complete the path within its constraints.
- Planning points are applied at equal arc-length distances along the curve.
- At each point from start to end, acceleration constraints are used to plan velocities at each point. Other constraints, like curvature constraining rotational accelerations and therefore linear velocities as well, are also taken into account.
- At each point from end to start, deceleration constraints are used to limit velocities at each point, making sure the entire path is traversable by the UAS.

Once the path has been generated, it is followed using a controller from a position at a given point in time inputs to velocity control outputs, which are fed into the autopilot. Once the vehicle is close enough to the USV (<15m), it will use a closed-loop position controller to reduce the position error between the USV and the UAS to 0, completing landing. This stage requires a certain height (to be determined through testing) so that landing happens in the correct manner. The control constraints on the UAS can be constrained even further if required for this last portion.

V. Performance evaluation

The experiments to evaluate autonomous takeoff and landing have been conducted in two phases as described below.

Phase 1 will be the comparative testing of the COTS GPS-based flight algorithms against the SSC PAC developed multi-modal flight algorithms for a stationary landing platform. The surrogate landing platform will be mounted on the bed of a pickup truck to simulate a stationary USV. This phase will record landing accuracy data for both versions of the flight algorithms. Flights using the COTS GPS-based flight algorithms will be executed first. A minimum of nine (9) flights will be conducted to measure the 3D spatial accuracy of the COTS GPS-based algorithms. Three (3) flights will be conducted against three (3) different GPS coordinates. If the GPS signal strength varies within the operating area, three (3) GPS coordinates of differing signal strengths will be chosen, otherwise GPS coordinates will be chosen so that the orientation of the landing platform allows the UAS to make an into-the-wind approach. Following completion of the COTS GPS-based flights, the SSC PAC multi-modal flight algorithms will be uploaded into the Vapor 55 UAS and the same nine (9) flight trails rerun to obtain similar accuracy measurements.

Phase 2 will be the evaluation of the SSC PAC multi-modal flight algorithms for a moving landing platform. The COTS GPS-based flight algorithms are not able to compensate for real time changes in landing coordinates. The surrogate landing platform from Phase 1 will be driven to simulate a USV in motion. A minimum of nine (9) flights will be conducted, first to see if the Vapor 55 UAS can land on a moving target and second, to measure the spatial accuracy with respect to the landing platform itself. If the operating area allows for into-the-wind landing approaches, the surrogate landing platform will be driven into-the-wind at 5 mph, otherwise the flight path will be chosen to give the longest approach path to enable the UAS enough time to calculate and execute its landing pattern. If the multi-modal flight algorithms achieve a high degree of success, additional flight excursions will be attempted with the landing platform moving either in a downwind direction and/or at a slightly higher speed.

A. *JIFX Experiments*

During the week of Aug. 10 our team participated in Joint Interagency Field Experimentation (JIFX 15-4) in Camp Roberts, CA organized by Naval Postgraduate School (NPS). The SSC PAC team used the exercise to collect USV/UAS interaction data, by simulating landing the Vapor 55 on the UAS landing platform built for the Wave Adaptive Modular Vessel (WAM-V) USV. In order to perform autonomous UAS landings additional sensors were added to each vehicle and tested. Cameras and LIDAR sensors were integrated into the landing platform to track a UAS in flight within close proximity to the USV. Cameras and LIDAR sensors were also integrated into the Vapor 55's payload package to localize and track the landing platform. During JIFX 15-4, a significant amount of data was collected for each sensor. Figure 5 shows LIDAR data obtained during Parrot UAS landing into the landing station. Figure 6 shows the same moment of Parrot landing seen by the landing station camera. Figure 7 shows the result of stereo camera detection and tracking algorithms where the Parrot UAS was correctly detected in the imagery and then tracked. This result gives the position estimate of the UAS obtained from the landing station camera data. Figure 8 shows the data of the landing station obtained from a camera onboard of Vapor 55 UAS. Figure 9 shows recent test of the WAM-V USV while Figure 10 shows the flight of Vapor 55 UAS.

B. *BtS Experiments*

"Breaking the surface" (BtS) is the world's first successful, multi-year, field training program that combines academic topics in marine robotics and robotics application areas and hands-on working experience in the sea, doing remote sensing and sampling for various ocean

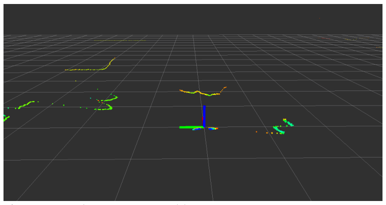

Figure 5: A smaller Parrot UAS & landing platform seen by lidar

Figure 6: Parrot landing

Figure 7: Stereo camera Parrot tracking

Figure 8: Vapor approach

Figure 9: USV with landing station

Figure 10: Vapor UAS

sciences. During BtS 2015 (October 4-11, Biograd, Croatia) SSC PAC will demonstrate autonomous takeoff and landing of modified VAPOR 55 UAS. The objective of the experiment is to test current iterations of SSC Pacific developed UAS flight algorithms under controlled conditions and compare them against the original equipment manufacturer's algorithms, for both a stationary and moving target. SSC Pacific is working to improve the effectiveness and the responsiveness of the Vapor 55 UAS algorithms from the solely GPS-based algorithms that come from the manufacturer, to combined GPS and optical algorithms (multi-modal algorithms) that can eventually be used to land the Vapor 55 UAS on a moving USV at sea. The commercial of the shelf (COTS) Vapor 55 UAS flight algorithms enable the aircraft to takeoff from a specific GPS position, fly to several GPS waypoints, and land at a specified GPS location. This navigational approach allows for controlled flight and landing using inexpensive COTS GPS technology with a positional accuracy error on the order of several meters depending on the operating area. Additionally, solely GPS-based flight algorithms can cause the UAS to "jump" during landing due to fluctuations in the GPS coordinates from one reading to the next. This type of flight control and level of accuracy is acceptable for autonomous land based operations or piloted operation, but is not sufficient for autonomous operations at sea.

This experiment will specifically measure two performance factors. The first is the landing accuracy for autonomous UAS flight operations against a stationary landing platform. Accuracy data will be compiled for both the COTS GPS-based and the multi-modal flight algorithms. The second is the ability for a UAS to autonomously land on a moving landing platform, and if successful, determine the level of accuracy with respect to the landing platform was achieved.

VI. Conclusions

A significant work has been performed to implement new capabilities and to enhance current hardware and software, as required by the initial specifications for the HAMMER system. The system modules and features have then been tested during a first set of in-field experiments performed at JIFX. The results, briefly described in this paper, show that all the different components of the system have been successfully integrated and that a significant amount of data was collected for each sensor.

In the coming months, new system components will be developed while some of those tested in the field will be improved, in particular, the UAS position estimation provided by the stereo camera to support the autonmous landing. This project will push the boundaries forward on autonomous UAS flight capabilities from solely GPS-based control to combined GPS and optical control, which will lay the groundwork for future cooperative operation of unmanned systems. Success in this research and development effort will add to the body of knowledge and advance future capabilities.

Autonomous UAS takeoff from and landing on a USV at sea will provide new capabilities for intelligence, surveillance, and reconnaissance (ISR) missions using cooperative unmanned systems. For example, a USV paired with the appropriate UAS could be deployed on long duration missions to collect and disseminate intelligence information, thereby enhancing maritime spatial understanding and situational awareness. The USV could independently identify signals of interest and autonomously launch and recover a UAS (or multiple UAS) to provide close-in reconnaissance. This information could then be relayed in real-time to designated watch stations while the UAS is in flight or disseminated upon recovery. With regards to global access, this same technology once validated could be incorporated into larger UAS platforms to provide over-the-horizon logistics support into austere or contested areas without jeopardizing human pilots. These algorithms would enable supplies to be delivered autonomously from a ship at sea.

ACKNOWLEDGMENT

This work was supported by the ONR grant N0001414WX00184 (Ms. Kelly Cooper, Code 33).

The authors gratefully acknowledge JIFX team for its valuable support and help during the experiments.

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