Test and Evaluation of Image-Based Navigation for Shipboard Landing on the MQ-8C Fire Scout Unmanned Aircraft System

Doug Duehring
Test Engineer
UX-24, U.S. Navy
Patuxent River, Maryland, USA

Brendan Egan
Test Pilot
UX-24, U.S. Navy
Patuxent River, Maryland, USA

Avinash Gandhe
Principal Research Engineer
Scientific System Company, Inc.
Woburn, Massachusetts, USA

ABSTRACT

From August 2022 to January 2023, Air Test and Evaluation Squadron Two Four (UX-24), the U.S. Navy's UAS test squadron, conducted ground and flight tests of the Image-Based Navigation for Shipboard Landing (INAV-SL) system on the MQ-8C Fire Scout UAS. The three-camera INAV-SL system was designed to optically detect standard flight deck markings and calculate relative position and orientation of the MQ-8C. The INAV-SL system was configured to collect data for comparison to the current landing system. No commands were input into the air vehicle's control feedback loop. A variety of approaches were conducted to fixed flight deck markings on an airfield taxiway and to the USS Jackson, an Independence class Littoral Combat Ship based out of San Diego, CA. The system demonstrated the ability to optically acquire and track the flight deck during approach and landing phases of flight with typical error of less than 2 ft.

INTRODUCTION

The MQ-8C Fire Scout UAS is a U.S. Navy system designed to provide sea-based Intelligence, Surveillance, and Reconnaissance (ISR) capability aboard Littoral Combat Ships (LCS) and Expeditionary Sea Base (ESB) ships. Currently, the MQ-8C relies solely on the UAV Common Automatic Recovery System (UCARS) for shipboard launches and landings. The UCARS is a radar-beacon based system that provides precise Air Vehicle (AV) and Touch Down Point (TDP) position values to the AV for tracking and guidance. Research into other landing systems is desired to counter the risk associated with UCARS failure and the subsequent inability to recover the AV, as well as to provide a capability for landing aboard ships not equipped with UCARS. The U.S. Navy Program Office for Multi-Mission Tactical UAS (PMA-266) has contracted Scientific Systems Company, Inc (SSCI) to support an Optical Back-Up Landing System (OBULS) for the MQ-8C. Their system is called the Image-Based Navigation for Shipboard Landing (INAV-SL). The terms "INAV-SL" and "OBULS" are used interchangeably throughout.

The autonomous launch and recovery of UAVs to a dynamic moving platform opens opportunities for a variety of mission profiles that would otherwise require a human in the loop in the terminal phase. Computer vision enables identification and tracking of known geometries or existing flight deck markings, reducing or eliminating the need for specialized equipment to be installed on the moving platform. Prior work by others have been successful at reducing UAV navigation errors to 2.2% of hover height using a $10 commercial off the shelf monocular camera aimed from 1 m (3.3 ft) at a stationary landing pad marked with binary identification markers that help with orientation (Ref. 1). Similar accuracy has been found when tracking more simply marked landing pads traversing in the horizontal plane (Ref. 2), in pitch, roll, and heave (Ref. 3), and even characterizing 6 DOF pose estimations simulating ship motion profiles in various sea states (Refs. 4, 5). Sanchez-Lopez has demonstrated landing a Rotomotion SR 200 (55 lb Group III UAS with 50 lb payload capacity) to a 6 DOF platform simulating the scaled motion of U.S. Navy Oliver Hazard Perry class frigate with the assistance of downward facing sonar once close to the ground (Ref. 6).

The INAV-SL system represents a new scale of operations on board the MQ-8C Fire Scout, a Group IV UAS that is currently operational and deployed on-board U.S. Navy ships. INAV-SL has been commercially tested from 2015 to 2020 in the maritime flight test environment on board crewed aircraft conducting manually flown approaches to a shipboard landing platform to evaluate the calculations and accuracy of the system. INAV-SL utilizes a three-camera system (more details later) which successfully demonstrated acquisition and tracking of the flight deck from increased distances that are not available from a single camera system. The flight deck stays in view of at least one camera from the normal approach angle until hovering directly over the landing spot.

This test and evaluation of the INAV-SL system focused on comparing the optically calculated positions and orientations

Presented at the Vertical Flight Society's 79th Annual Forum & Technology Display, West Palm Beach, FL, USA, May 16-18, 2023.

to a truth source system. The INAV-SL and truth source system were configured to collect the same data during approaches and landings, allowing the output information to be compared directly to each other.

Further testing of the INAV-SL system is required before it can be fully incorporated into the MQ-8C system architecture. With the collected data set, guidance and control logic response to system's outputs may be simulated to ensure compatibility. Once the MQ-8C is configured to utilize the optically calculated position in the control loop, a full test project will be required to quantify the performance of the system in both the land-based and shipboard environments. If the system proves capable conducting landings and approaches in the control loop, the next step in its incorporation and release to the fleet will be to conduct operations to platforms not outfitted with the UCARS system.

MQ-8C LANDING SYSTEM OVERVIEW

The MQ-8C Fire Scout is an Unmanned Aircraft System (UAS) single-engine helicopter derivative of the Bell 407 helicopter produced by Northrop Grumman Corporation. It is equipped with a Rolls-Royce model 250-C47E turbo-shaft engine, landing skids, a composite soft in-plane flex beam four-blade main rotor, and a two-blade teetering tail rotor. The MQ-8C has a maximum Gross Weight (GW) of 6,000 lb and is designed to remain on station for over 5 hours up to 150 nm with a top speed of 130 kts. The AV is equipped with two integrated and Embedded Global Positioning Systems (GPS)/Internal Navigation Systems (INS) (EGI). The aircraft's computer and control systems consist of two redundant Vehicle Management Computers (VMCs) which monitor the aircraft's subsystems status, data messages, and commands. The computer and control subsystem is controlled and managed by the VMC and the Guidance, Navigation, and Control (GNC) software. AV router switches are used to provide a form of Ethernet communication between the EGI's, VMC's, payloads, and other AV subsystems.

The MQ-8C Fire Scout is capable of conducting both shore-based and ship-based missions. For shore-based missions, the AV uses the onboard EGIs for absolute navigation, to include launches and recoveries, and is controlled by the GNC control logic. GPS waypoints are set by the Air Vehicle Operator (AVO) using a mission plan which is then uploaded to the AV.

For ship-based operations, GPS waypoints are flown with respect to the ship, also known as relative navigation. These waypoints are also set within the mission plan and allow the AV to operate in close proximity to the ship while the ship is transiting through the water. Relative navigation uses the same GNC control logic used for absolute navigation and sets up the AV on final approach to transition to UCARS recovery guidance and control.

The UCARS subsystem consists of two primary systems: the Airborne Subsystem (AS) and the Tracking Subsystem (TS). The AS is a pulse radar system that provides a point source of RF energy defining the relative location of the AV from the TS. The TS is a radar pedestal equipped with an inertial measurement unit (IMU), antenna, camera, and interconnecting cables to the ship and MCS. The TS stabilizes the UCARS reference frame/TDP using the ship motion sensor, and calculates the current AV and TDP position relative to the stabilized frame/TDP. Both the AV and TDP position data are sent to the AV's VMC and GNC via datalink.

Recovery Guidance and Control

The MQ-8C uses a multi-staged approach to landing in the shipboard environment, shown in Figure 1, in order to transition from relative navigation to recovery guidance and control. The Initial Approach Fix (IAF) is the first relative waypoint on the approach route, followed by the terminal approach waypoint. During the transition from IAF to the terminal approach waypoint, UCARS acquires and tracks the AV. Upon acquisition, the AV transitions from relative navigation to UCARS guidance. During UCARS guidance, the GNC uses UCARS AV position to command the AV. If UCARS acquisition is unsuccessful by the terminal approach waypoint, the AV will waveoff and attempt the approach again from the IAF.

Once the AV reaches recovery perch the GNC switches to UCARS control to command the AV through the remainder of the approach and recovery. During UCARS control, UCARS is providing the GNC with AV and TDP position measurements with respect to the stabilized frame and ship heading measurements relative to true north. The AVO gives a land command, and the AV proceeds to the high hover and low hover positions under UCARS guidance and control.

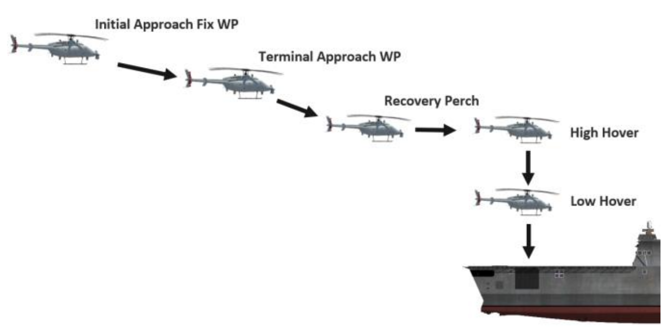

Figure 1: MQ-8 Shipboard Approach Waypoint Overview

The recovery perch position is typically 100 ft aft of the TDP and 30 ft above the TDP, but can be adjusted within the mission plan. The high hover position is located directly over the TDP, and is automatically set to the same altitude as recovery perch within the mission plan. The low hover position is also directly over the TDP and is programmed to 15 ft above the TDP. The low hover altitude is not adjustable.

Data Requirements

In order to evaluate and compare the INAV-SL system performance to the truth source, INAV-SL must provide the following data to the VMC:

X_{rd}, Y_{rd}, Z_{rd}: AV position measurements relative to the stabilized TDP.

X_{11}, Y_{11}, Z_{11}: TDP position measurements relative to the stabilized TDP.

$\Theta_{\text{Approach Heading}}$: Approach heading command relative to true north.

INAV-SL OPTICAL LANDING SYSTEM TECHNOLOGY OVERVIEW

The INAV-SL optical landing system was designed to use optical imaging sensors to analyze the location and orientation of the landing deck relative to the aircraft and provides precise relative position estimates to facilitate safe approach and landing. INAV-SL calculates the relative position of the aircraft based on identification of landing deck markings by cameras installed on the aircraft. INAV-SL uses a computer vision technique called Planar Homography to estimate the relative position between the aircraft and the deck. Given standard flight deck markings specified and implemented on a platform, the technique can match the observed pattern to a template model. The homography matrix captures the 6 degree of freedom (DOF) pose (translation and orientation) of the deck pattern in the camera coordinate frame. The cameras were calibrated to combine the homography-calculated pattern orientation with the AV's INS attitude to provide a camera-based relative position estimate, known as Deck Relative Navigation (DRN). The DRN can be further converted to a ground-based coordinate frame.

A Deck Motion Estimation (DME) algorithm was developed by SSCI to provide a stabilized TDP calculation. DME is based on ship translation and orientation relative to a stabilized frame. The DME tracks the inertial position and velocity of the TDP from the calibrated camera-based measurements. A filter is applied to separate steady-state translation of the TDP from ship-based oscillations. The filtered signal is the stabilized deck frame (X_{rd}, Y_{rd}, Z_{rd}) and the residual signal is the position of the TDP in that stabilized deck frame (X_{11}, Y_{11}, Z_{11}). The approach heading command, Θ, is derived from the orientation of the stabilized deck frame.

In addition to the position and heading measurements, the INAV-SL system also sends a detailed status and system health message to the VMC, which includes a data valid flag. The validity of the INAV-SL message is determined by two factors: the uncertainty in the relative position estimates from the DME filter and the amount of elapsed time since the last DRN measurement. Since the converged DME filter continues to report position estimates after DRN tracking is lost, the DRN timeout feature is implemented to ensure the data is marked as invalid shortly after loss of DRN tracking. Further technical details on the INAV-SL system design and development can be found in Reference 7.

INAV-SL MQ-8C INTEGRATION

The INAV-SL design as integrated onto the MQ-8C Fire Scout is shown in Figure 2. The system hardware used for this effort were early, Generation 1, prototypes comprising of a Vision4CE TRUPER 110CE Processor, three Commercial-off-the-shelf (COTS) 5-megapixel cameras with custom packaging produced by Optics 1, Inc., and a power and Ethernet wiring harness. The processor was installed inside the fuselage. The three cameras are referred to as the glideslope camera, perch camera, and hover camera, based on where in the approach they will have the flight deck TDP in their field of view (FOV). The glideslope camera was installed on the nose of the AV and bolted to the mounting bracket used for the EO/IR camera. The perch and hover camera were mounted on a singular mount which attached to existing bolts designed for the Bell 407 cargo hook on the underside of the AV. Each camera had custom lenses and mounting depression angles with respect to the aircraft frame to maximize effective FOV of the system, shown in Table 1.

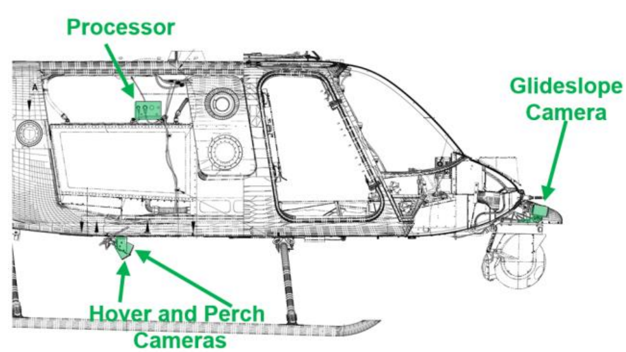

Figure 2: INAV-SL system integrated onto the MQ-8C Fire Scout airframe.

Table 1: INAV-SL Camera Configuration

Camera	FOV (long axis)	Depression Angle
Hover Camera	92.2°	60.7°
Perch Camera	37.5°	25.5°
Glideslope Camera	21.4°	9.5°

The INAV-SL system interfaces with the AV through Ethernet and power connections. Power supplied at 28V is provided to the INAV-SL processor and cameras via the AV's Power Distribution Module (PDM). Each camera communicates with the processor via gigabit Ethernet, and the processor communicates with the MQ-8C through the AV router switch. The router switch allows Ethernet communication to/from the processor and VMC. The VMC receives the necessary INAV-SL data packets from the processor, and in return sends INS data packets to the processor.

Flight Test Modifications

Modifications to the originally proposed INAV-SL mounting designs were needed to ensure all exposed components and fasteners have two locking features to prevent Foreign Object Damage (FOD) and Things Falling Off Aircraft (TFOA) during flight. The UX-24 test team and SSCI worked with the Naval Air Warfare Center Aircraft Division (NAWCAD) Prototyping Instrumentation and Experimentation (PIE) division to design, analyze, and manufacture fully encompassed camera enclosures, referred to as "trash-can" enclosures. PIE's camera enclosures retain all Original Equipment Manufacturer (OEM) camera components and hardware, as shown in Figure 3.

Figure 3: PIE's Perch and Hover camera enclosure and bracket assembly with SSCI's cameras enclosed, as mounted on the MQ-8C.

To accommodate routing for the data and power cables, PIE created a new weapons mount plug insert using 3-D scanning and printing technology. The weapons mount plug is located on the side of the AV below the rear doors. The weapons mount plug, primarily used for external loads, allowed access to inside the airframe and supplied a point of entry to route the perch and hover cameras power and Ethernet cables from the underside of the AV to inside the fuselage. The cables were routed through a 3-D printed insert and installed in place of the standard weapons plug insert. The insert was weatherproofed using AMS-S-8802 sealant.

To accurately evaluate INAV-SL system performance, a replica LCS landing deck pattern was painted onto the test taxiway at Webster Outlying Field (WOLF) in St. Inigoes, MD, shown in Figure 4. The deck markings consist of a 1 ft wide centerline, a 1 ft wide circle with a radius of 12 ft, and a solid white center circle with a radius of 2 ft. The center of the painted landing pattern was positioned directly on top of the normal TDP.

Figure 4: Replica LCS painted deck marking located on the taxiway at WOLF.

The INAV-SL system was configured for testing to provide valid position measurements when the navigation filter determines that the uncertainty of the position estimates is less than 4 feet.

SHORE-BASED TEST AND EVALUATION

Shore-based flight testing was conducted at Webster Outlying Field (WOLF), St. Inigoes, Maryland from August to December 2022. Data from 78 approaches to the shore-based TDP were analyzed. Testing was conducted in three phases: Data Verification and Camera Calibration, AV Position Measurement Evaluation, and Induced AV Motion Evaluation.

Data Verification and Camera Calibration

Initial data verification was conducted on the ground to ensure the INAV-SL processor was sending and receiving compatible data packets to and from the AV's VMC. The VMC was also checked to verify recording of the INAV-SL data.

Software regression testing consisted of 5 approaches with the INAV-SL system powered on and collecting data. Software regression verified no impact to validated software logic. The data collected during the regression flights was used to calibrate the cameras to account for installation position and orientation errors relative to the aircraft INS frame. The calibration used surveyed points on the ground, measured by the cameras in flight, to determine the relative orientation between the camera and aircraft INS frame.

AV Position Measurement Evaluation

The AV position measurement evaluation compared the truth source and INAV-SL AV position and heading measurements during approaches to the shore-based TDP. Differences were calculated by subtracting INAV-SL position measurements from truth source position measurements in all axes. INAV-SL tracking performance was only evaluated when the system reported data as valid. Acquisition range and tracking performance were also evaluated. A combination of approaches at varying glideslopes, recovery perch altitudes, and TDP locations were conducted. The combinations of approach profiles are shown in Table 2.

Table 2: Adjustable Parameters within the Approach Profile

Parameter	Values Tested
Glideslope (deg)	High, Low, Standard
Recovery Perch Altitude (ft)	30, 50, 75, 100
TDP Location	Ideal, Middle, Center

The glideslope for a standard recovery profile varies, and is dependent on the altitude of the recovery perch waypoint. In addition to the standard approach altitude of 30ft, approaches were flown to an altitude of 50ft, 75ft and 100ft. High and low glideslopes and varying recovery perch altitudes were evaluated to characterize INAV-SL performance and limitations.

Three targeted TDPs were used to command the AV center of gravity to land at the center spot, middle spot, and ideal spot shown in Figure 5. The center spot targets the center circle of the landing pattern. The middle spot targets 7 ft aft of the center circle, and the ideal spot targets the aft intersection of the centerline and the 12 ft radius outer circle. Adjusting the TDP location allows for more/less of the deck markings to be within the Field of View (FOV) of the Perch and Hover camera during the descent to the deck. For instance, moving the aircraft aft to the ideal spot allows the cameras to see the intersection of the centerline and outer circle while at the low hover position, as shown in Figure 6. This was done to optimize tracking to touchdown. The typical landing spot on board U.S. LCS ships is aft of the ideal spot.

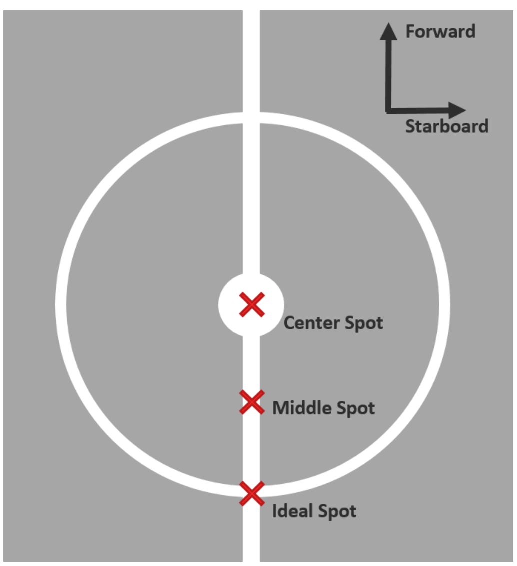

Figure 5: Touch Down Point Locations for Shore-based Testing

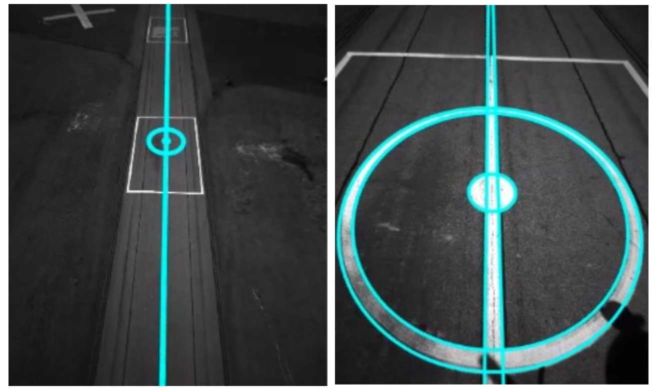

Figure 6: Still image from the Hover camera with the INAV-SL solution imposed over the landing area at the recovery perch position (left) and the low hover position (right) when conducting an approach to the ideal spot.

The acquisition range was determined by the x-axis range at which the INAV-SL system reports the data as valid, as measured by the truth source. The acquisition range of all combinations of glideslope and recovery perch altitudes is shown in Figure 7. The average acquisition range across all flight events was 880 ft. The INAV-SL system software was tuned and configured throughout shore-based flight tests to refine system performance. During the last test flight, the system averaged an acquisition range of 1077 ft. The maximum acquisition range seen was 1,253 ft, which occurred on a high glideslope approach. Generally, approaches with higher recovery perch altitudes and higher glideslopes acquired sooner on the approach than lower recovery perch altitudes and lower glideslopes.

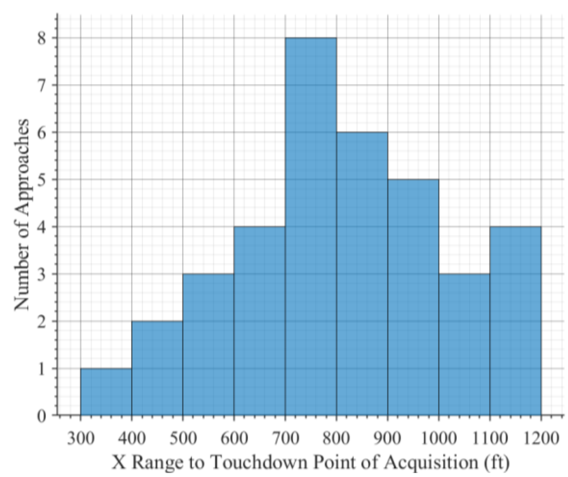

Figure 7: Longitudinal (X) Range of INAV-SL Acquisition

A direct comparison between INAV-SL and truth source approach heading command, ϴ, was used to determine heading difference. The truth source approach heading for shore-based approaches is determined by the truth source navigation system and is aligned with the fixed taxiway.

INAV-SL calculates the approach heading based on the orientation of the calculated stabilized deck frame.

Figure 8 shows the average approach heading difference taken across 33 approaches from acquisition to 1 sec before touchdown. The average heading difference was centered at about 0.5 degrees, while the majority of data is within +/- 3 deg. Results indicate a possible heading offset bias. Potential causes of heading biases could be a result of the INAV-SL system calibration with the MQ-8C platform and/or alignment differences between the truth source and the approach taxiway.

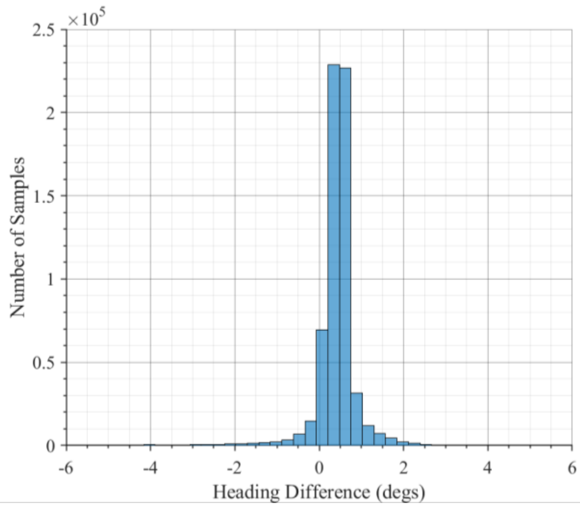

Figure 8: Heading difference from acquisition to 1sec from touchdown.

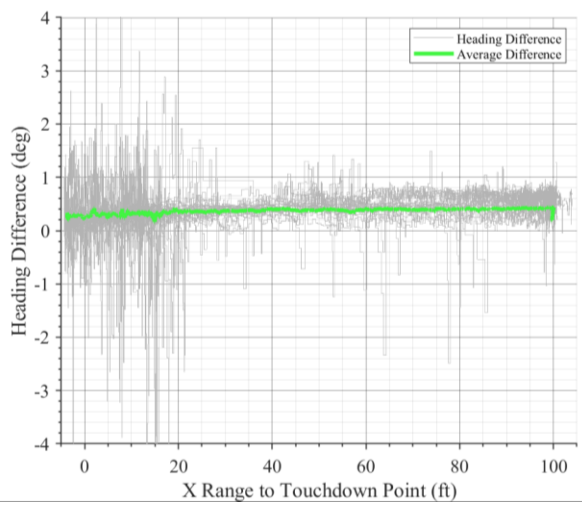

Figure 9: Heading difference from recovery perch to high hover, as a function of distance from the touchdown point.

The approach heading difference between recovery perch and high hover is shown in Figure 9 for the 33 approaches along with the average heading difference. Approach heading measurements throughout this portion of the approach were accurate to within 3 deg. At the high hover position, there is an increase in reported heading difference outliers. Overall, INAV-SL heading measurements performed well compared to the truth source throughout all phases of the approach.

INAV-SL AV position measurements, X_{rd}, Y_{rd}, Z_{rd}, were evaluated in the longitudinal (X), lateral (Y), and vertical (Z) axes to the truth source. All INAV-SL position estimates in the X axis are corrected based on the appropriate TDP location. A total of 31 approaches were used for analysis of position measurement accuracy. Shortly after acquisition, INAV-SL position measurements differed up to 50 ft. There are two contributors to the higher initial difference. First, INAV-SL has higher initial errors before converging on a solution. Second, angular alignment biases between the INAV-SL and truth source systems result in larger distance differences at longer range as the radials expand.

Prior to recovery perch and throughout the rest of the approach, the INAV-SL position solution converges to within +/- 3ft of the truth source. Figure 10 shows the average difference between position measurements across the 31 approaches when the AV transits from the recovery perch to high hover position in each axis. Similar to the approach heading bias, INAV-SL position differences show biases in the longitudinal and lateral axis. The longitudinal (X) axis has an average difference of 2.5 ft aft of truth source measurements, and the lateral (Y) axis has an average difference of 1.5 ft port of truth source measurements. In the vertical (Z) axis, INAV-SL tracks slightly lower than truth source position measurements at the recovery perch position, but the vertical axis tracks slightly above truth source position measurements at the high hover position. Biases in each of these axes could be a result of many factors, to include possible INAV-SL calibration, lever arm errors, and/or inconsistencies with the approach taxiway and truth source configuration/heading alignment.

From high hover to landing, INAV-SL provides the same level of accuracy as the previous phase as the AV descends to the ground. In the shore-based environment, the INAV-SL system maintained visual acquisition of the landing area to within 5 ft above the ground, roughly 1 second before touchdown. Once visual acquisition is lost, the INAV-SL system continues to provide position measurements using the INS data provided by the AV. Since the landing area is stationary for shore-based testing, the INS position measurement solution is just as accurate as the visual position measurement solution. Figure 11 shows the average position difference in the vertical (Z) axis for 20 approaches from the low hover position to touchdown as a function of height above touchdown.

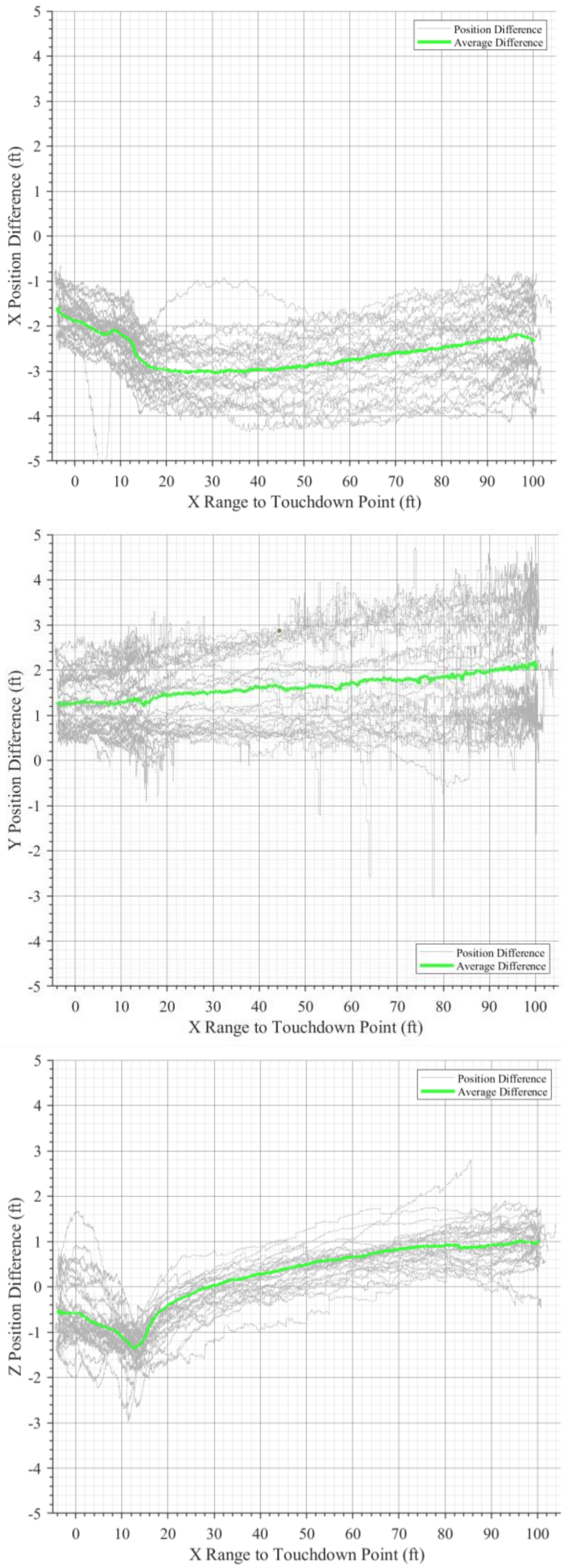

Figure 10: Longitudinal (X), lateral (Y), and vertical (Z) position differences when the AV is transiting between the recovery perch and high hover position.

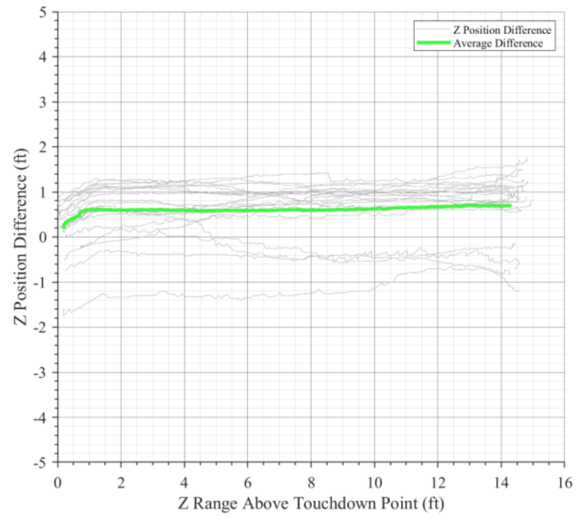

Figure 11: Average vertical position differences from low hover position to touchdown.

Induced AV Motion Evaluation

The purpose of inducing AV motion during testing was to evaluate INAV-SL DRN and DME position measurements when the AV is exposed to exaggerated motion. AV motion was executed using pre-programmed MQ-8C "flight test only" commands, which induce frequency sweeps in an individual pitch, roll, or yaw axis of the MQ-8C control logic. Frequency sweeps were conducted during an in-flight 100 ft hover at the recovery perch and high hover positions. Testing was to verify that the TDP position measurement output, X_{11}, Y_{11}, Z_{11}, is zero since the TDP and the landing area are stationary.

Initial AV motion testing indicated that some AV motion was bleeding into INAV-SL estimates of the TDP position. The AV position data, obtained from the VMC INS message, was not suitable for use by INAV-SL to separate TDP motion from AV motion. After consultation with Northrop Grumman's GNC team, a software change was made to incorporate the velocities provided in the INS message, rather than positions, to characterize AV motion. This change resulted in significant improvement in the INAV-SL estimates of TDP position.

SHIPBOARD TEST AND EVALUATION

Shipboard MQ-8C flight testing was conducted onboard USS Jackson (LCS 6) at sea in January 2023 (Figure 12). INAV-SL data collection was performed while conducting approaches and landings. Unlike the shore-based testing, this testing allowed for evaluation of the system's ability to calculate the position and orientation of the flight deck during the approach. The shipboard environment introduces a new set of test variables to the AV and the INAV-SL system. Wind over the ship's superstructure introduces turbulence to the AV, especially from the high hover position to touchdown.

Ship motion also now plays a role in the control logic, with the AV compensating for TDP motion from low hover to touchdown. More drastic pitch/roll/yaw attitude changes occur to maintain safety margins between the AV and moving flight deck. No major software changes were made from shore-based testing to the INAV-SL system for this testing. A minor setting change to initialization logic was made to facilitate re-acquisition of the landing markings during an approach if acquisition is lost. This change was primarily made to maximize the amount of valid data collected during the flight event for later analysis.

Figure 12: MQ-8C Fire Scout landing onboard LCS-6

The shipboard testing profile was limited to the current fleet approved mission plan and TDP location. The approved mission plan consisted of a 30 ft recovery perch and high hover altitude. The approved TDP location is located aft of the center landing circle. Additionally, daily post-flight changes to the INAV-SL system configuration were unavailable during the shipboard test effort.

Shipboard Results

A total of 27 approaches were flown to the TDP with INAV-SL collecting data. For the purpose of this analysis, 10 approaches that produced the most consistent data all the way through touchdown were selected to compare with the truth source. Results shown are a preliminary overview of system performance and further analyses is still being conducted.

Acquisition ranges varied for each approach in the shipboard environment. Out of the 10 analyzed approaches, the average acquisition range was 771 ft. Many factors contribute to when INAV-SL acquires, such as environmental/weather conditions, sun position/time of day, and ship orientation with respect to the sun. While more recent INAV-SL Generation 3 cameras are equipped with polarizing filters and mechanical irises to address issues related to these factors, the Generation 1 cameras used during these flight tests did not have these features and therefore, some variability was observed over different flight periods. Separating the 10 samples into the three flight periods in which the data was collected shows a difference in average acquisition distance as seen in Table 3. In-flight visibility was consistent, but the time of day and orientation of the ship with respect to the sun varied between the three flight periods. Post-flight video of the glideslope and perch camera during the first flight period showed glare off the water and flight deck, reducing the system's ability to acquire at range, while the third flight period had the best flight conditions for test with an observed maximum acquisition range of 1200 ft.

Table 3: INAV-SL Shipboard Acquisition Ranges Based on Day and Flight Period

Day	Flight Period	Time of Day (L)	# Approaches	Average Acq. Range (ft)
1	1	1500	3	373
2	2	1200	3	770
2	3	1400	4	1070
Total			10	771

The shipboard approach heading difference is shown in Figure 13. Results show that the INAV-SL provided consistent heading measurements compared to the truth source from acquisition to touchdown within +/-2 deg; however, results indicate a bimodal distribution with peaks at approximately +/-1 deg and very few samples reported with 0 deg heading difference. It is hypothesized that these heading biases are a result of inconsistencies in the two navigation systems which feed the truth source approach heading parameter however, additional analysis is needed to determine the cause.

The differences between position measurements was evaluated from the recovery perch position to touchdown. Results showed similar difference dispersion compared to shore-based results. The longitudinal (X) and lateral (Y) axis produced consistent position differences of +/- 3 ft while still indicating a bias of 1.5 to 2 ft aft and 1 ft port of truth source measurements, respectively. The vertical (Z) axis produced an average position difference of roughly 1ft, ranging +/- 2 ft position difference, indicating a consistent bias lower than truth source measurements.

Due to the motion of the ship, INAV-SL collected valuable data regarding the system's ability to measure the landing deck. The truth source and INAV-SL both measure the motion of the TDP with respect to the stabilized frame. The motion of the TDP as measured by the truth source and INAV-SL for the longitudinal (X), lateral (Y), and vertical (Z) axis for one approach is shown in Figure 14. The oscillations in the figure are a result of period ship motion induced by the sea state. Overall, there is a high level of correlation between the oscillations measured by the two systems. The highest degree of accuracy is seen in the vertical (Z) axis which requires the highest fidelity to provide for a controlled descent to the flight deck.

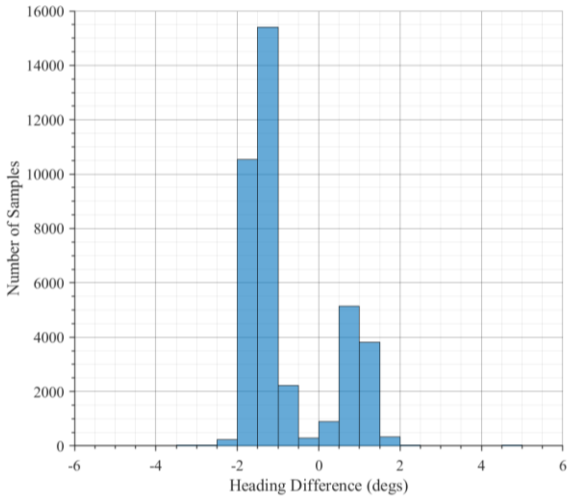

Figure 13: Shipboard approach heading difference from acquisition to touchdown.

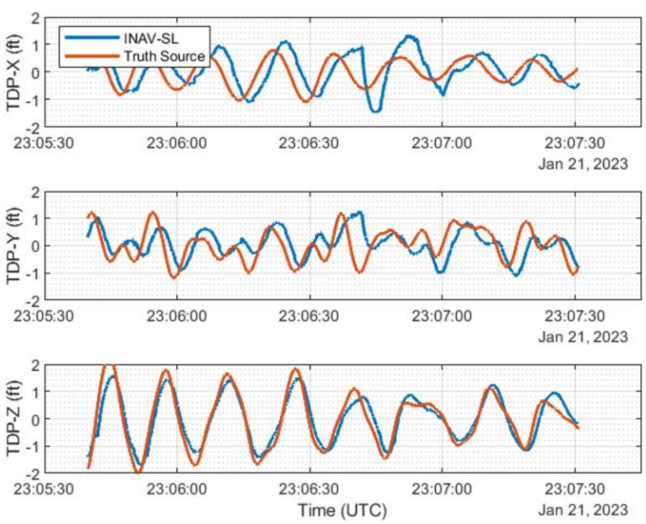

Figure 3: Longitudinal (X), lateral (Y), and vertical (Z) TDP measurements during an approach between recovery perch and high hover position.

The differences in TDP measurements between the truth source and INAV-SL was evaluated from the recovery perch position to the low hover position. Figure 15 shows the majority of INAV-SL TDP measurements were within +/- 2 ft for the longitudinal and lateral axes and within +/- 1 ft in the vertical axis. No biases were seen in the TDP data, with all three TDP difference averages < 0.1 ft in each of the three axes.

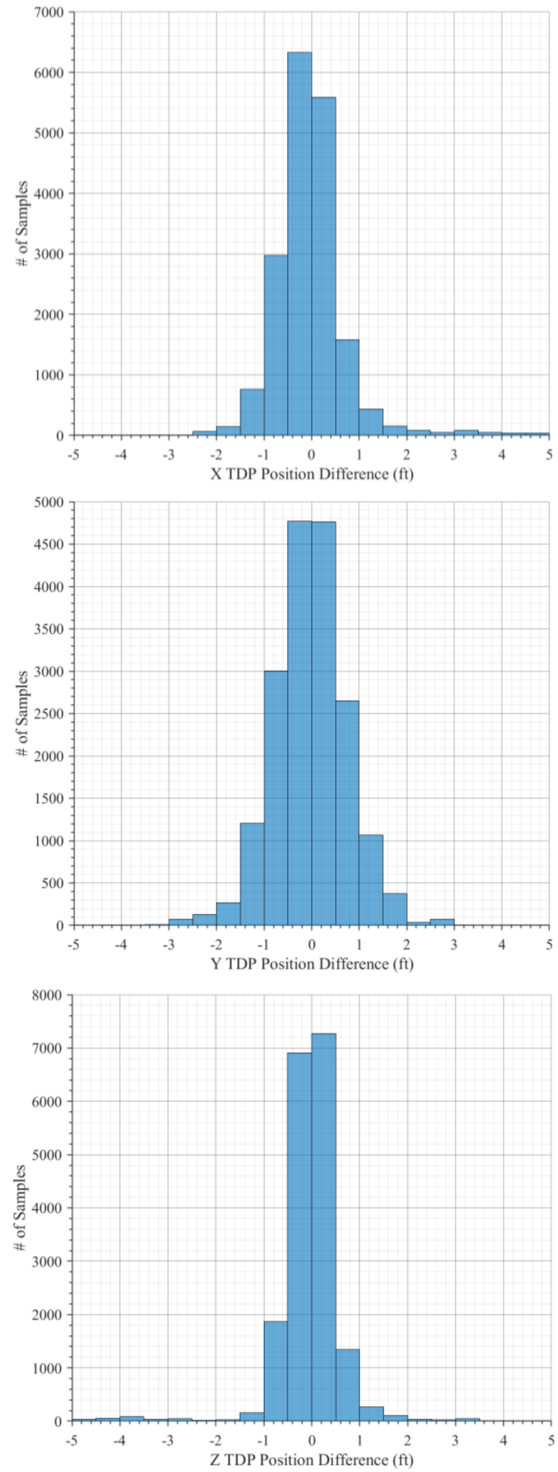

Figure 15: Shipboard longitudinal (X), lateral (Y), and vertical (Z) TDP position differences from the recovery perch to low hover position.

Since the system was configured to continue to report TDP position measurements using the INS for 3 seconds after visual acquisition lost, TDP measurements below low hover were not included in the overall evaluation. For shipboard approaches, INAV-SL lost visual acquisition of the landing area during the descent from low hover to touchdown, less than 10 ft above the touchdown point. Figure 16 shows the INAV-SL TDP measurements drift away from truth source reported TDP position as the visual tracking is lost and the system enters INS only mode. Operationally, the INAV-SL system would report measurements for <0.5 seconds after visual acquisition is lost to prevent unwarranted data and commands to the AV.

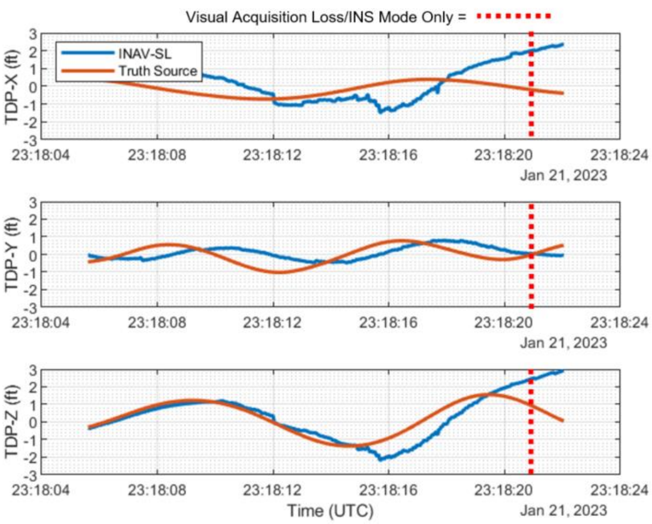

Figure 16: Shipboard longitudinal (X), lateral (Y), and vertical (Z) TDP measurements from the start of the low hover position to touchdown.

CONCLUDING REMARKS/FUTURE WORK

Shore-based and shipboard flight testing proved that SSCI's INAV-SL system is a viable option as an optical landing system to prepared surfaces in both shore-based and shipboard environments. The system integrates seamlessly to provide the nearly same quality data that is currently provided by the current landing system on the MQ-8C. In the shore-based environment, calibration of the system brought optical navigation solutions to within 2 deg of heading and +/- 3 ft in all position axes during relevant portions of the approach to landing. Testing in the shipboard environment demonstrated similar results for AV position calculations and high correlation for the TDP motion calculations in the stabilized reference frame. Overall, results showed that INAV-SL tracking performance of the TDP and the AV positions performed well compared to the truth source system. Future work is expected to further improve the system with updated software and hardware to make the system more reliable and robust. Data collected during this test effort will be used to enhance computer models and simulations to verify system performance in the lab prior to future flight tests. The simulator environment will ensure the output of the INAV-SL system is fully compatible with the aircraft's GNC logic before conducting in-the-loop flight testing with the ultimate goal of releasing INAV-SL to fleet operators.

Author contact:
Douglas Duehring douglas.a.duehring.civ@us.navy.mil
Brendan Egan brendan.c.egan2.mil@us.navy.mil
Avinash Gandhe avinash.gandhe@ssci.com

ACKNOWLEDGMENTS

The INAV-SL testing was conducted by U.S. Navy Air Test and Evaluation Squadron Two Four (UX-24) under the direction of the Naval Air Systems Command's Program Office for Multi-Mission Tactical Unmanned Aerial Systems (PMA-266). The INAV-SL system is furnished by Scientific Systems Company, Inc (SSCI).

Special thanks to the Wardroom and Crew of the USS Jackson (LCS 6) for hosting the MQ-8C Test Team in port and at sea off the coast of San Diego, CA.

REFERENCES

1. Liu, X., Zhang, S., Tian, J., and Lui, L., "An Onboard Vision-Based System for Autonomous Landing of a Low-Cost Quadrotor on a Novel Landing Pad," Sensors, 2019, 19(21), 4703.
2. Nakamura, T., Haviland, S., Bershadsky, D., and Johnson, E.N., "Vision-Based Optimal Landing on a Moving Platform," AHS 72nd Annual Forum, West Palm Beach, FL, May 17-19, 2016.
3. Holmes, W.K., and Langelaan, J.W., "Autonomous Ship-board Landing using Monocular Vision," AHS 72nd Annual Forum, West Palm Beach, FL, May 17-19, 2016.
4. Yang, S., Scherer, S.A., and Zell, A., "An Onboard Monocular Vision System for Autonomous Takeoff, Hovering and Landing of a Micro Aerial Vehicle," J Intell Robot Syst 69, 2013, pp. 499-515.
5. Truskin, B.L., and Langelaan, J.W., "Vision-based Deck State Estimation for Autonomous Ship-board Landing," AHS 69th Annual Forum, Phoenix, AZ, May 21-23, 2013.
6. Sanchez-Lopez, J.L., Pestana, J., Saripalli, S., and Campoy, P., "An Approach Toward Visual Autonomous Ship Board Landing of a VTOL UAV," J Intell Robot Syst 74, 2014, pp.113-127.
7. Gandhe, A., Morrison, J., Sehgal, A., Kyser, D., "Design and Development of Autonomous Optical Launch and Recovery System for MQ-8 Fire Scout," 8th Biennial Autonomous VTOL Technical Meeting & 6th Annual Electric VTOL Symposium, Mesa, AZ, Jan.28-Feb.1, 2019.