Contract # N00014-14-C-0004

Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

Progress Report (CDRL A001)

Progress Report for Period: July 10-Oct 10, 2015

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) initiative in Advanced Handling Qualities for Rotorcraft.

Landing a rotorcraft on a moving ship deck and under the influence of the unsteady ship airwake is extremely challenging. In high sea states, gusty conditions, and a degraded visual environment, workload during the landing task begins to approach the limits of a human pilot's capability. It is a similarly demanding task for shipboard launch and recovery of a VTOL UAV. There is a clear need for additional levels of stability and control augmentation and, ultimately, fully autonomous landing (possibly with manual pilot control as a back-up mode for piloted flight). There is also a clear need for advanced flight controls to expand the operational conditions in which safe landings for both manned and unmanned rotorcraft can be performed. For piloted rotorcraft, the current piloting strategies do not even make use of the available couplers and autopilot systems during landing operations. One of the reasons is that, as the deck pitches and rolls in high sea states, the pilot must maneuver aggressively to perform a station-keeping task over the landing spot. The required maneuvering can easily saturate an autopilot that uses a rate limited trim system. For fly-by-wire aircraft, there is evidence that the pilot would simply over-compensate and negate the effectiveness of a translation rate command/position hold control mode. In addition, the pilots can easily over-torque the rotorcraft, especially if they attempt to match the vertical motion of the deck.

This project seeks to develop advanced control law frameworks and design methodologies to provide autonomous landing (or, alternatively, a high level of control augmentation for pilot-in-the-loop landings). The design framework will focus on some of the most critical components of autonomous landing control laws with the objective of improving safety and expanding the operational capability of manned and unmanned rotorcraft. The key components include approach path planning that allows for a maneuvering ship, high performance station-keeping and gust rejection over a landing deck in high winds/sea states, and deck motion feedback algorithms to allow for improved tracking of the desired landing position and timing of final descent.

2. Activities this period

Task 1 - Plant and Disturbance Model

During this reporting period, FLIGHTLAB flight dynamics models for the light class (similar to the FireScout) and a heavy class (similar to the H-53) aircraft have been developed. The light class model consists of a 4-bladed blade element main rotor and the heavy class model consists of a 7-bladed blade element main rotor model. Both models use unsteady airloads and 6-state Peters-He's finite state dynamic wake model. It simulates fully articulated rotor dynamics with geometrically exact multi-body dynamics modeling that includes flap and lead-lag degrees of freedom. The unsteady airloads model allows for the effects of blade yawed-flow, pitch rate, and stall delay due to the blade rotation. The airframe model consists of a fuselage, empennage, sensors, and landing gear. The fuselage is modeled using nonlinear 6-DOF dynamics and the fuselage airloads are computed using empirical table look-up as a function of fuselage angle of attack and angle of sideslip. The empennage consists of both left and right horizontal stabilizer as well as a vertical fin. The sensor model outputs the aircraft body attitude and rate information for use by the flight control system. The landing gear system model are modeled using a full nonlinear spring/damper formulation. The landing gear model also considers ground friction and tire deformation effects and allows for interaction with a moving surface in order to support shipboard landing simulation. The light weight class helicopter model has been distributed by ART to NAVAIR and Penn State team members and the heavy weight class model will be delivered soon. We have currently implemented two sets of ship motion "SCONE1" and "SCONE2" corresponding to "low" and "medium" deck motion respectively.

Task 4. Dynamic Inversion Control Design

The dynamic inversion control laws were designed for the light class simulation model. This process was rather seamless, as the control gains and inverse model are set by a design script that was transferrable to the light class simulation with virtually no modification. In addition, the Control System Graphical Editor model of the control system could be ported to the light class sim model with only minor modifications in order to interface with the control inputs of the helicopter model.

Figure 1 – Figure 4 show some representative simulation results with the light class simulation model including an approach and landing with the SCONE2 heave dominated ship motion. Figures 3 and 4 show landing scatter plots for 30 different cases using the deck tracking landing sequence. The results show similar behavior and performance as the medium class simulation presented in the last reporting period. One notable difference is the overshoot of the landing spot seen in Figure 1. It is hypothesized that the light class simulation is more sensitive to the flow blockage effects in the ship airwake.

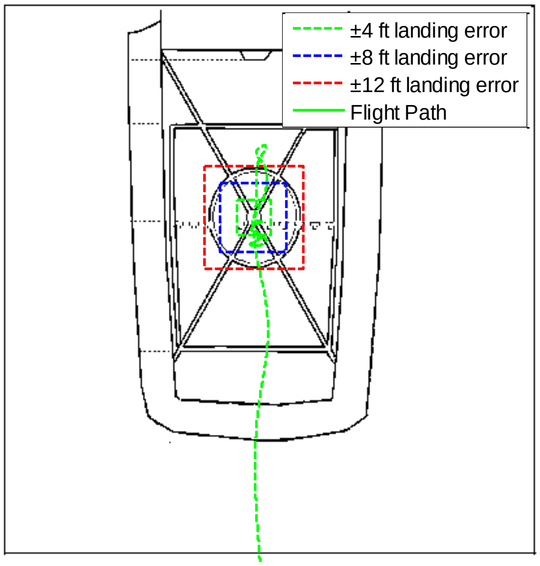


Figure 1. Landing Trajectory

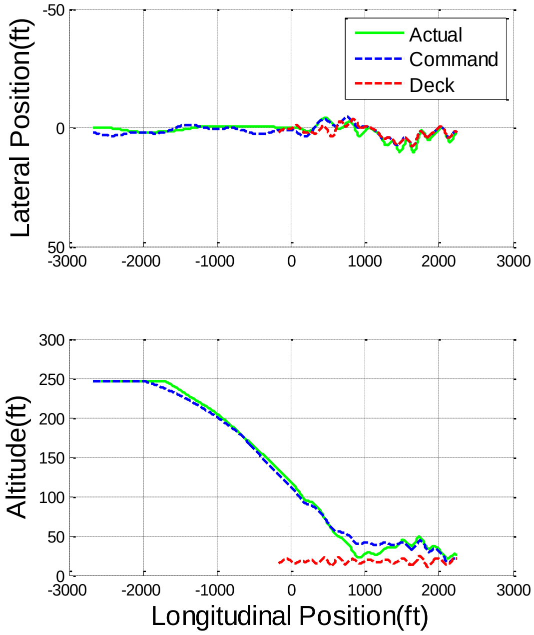
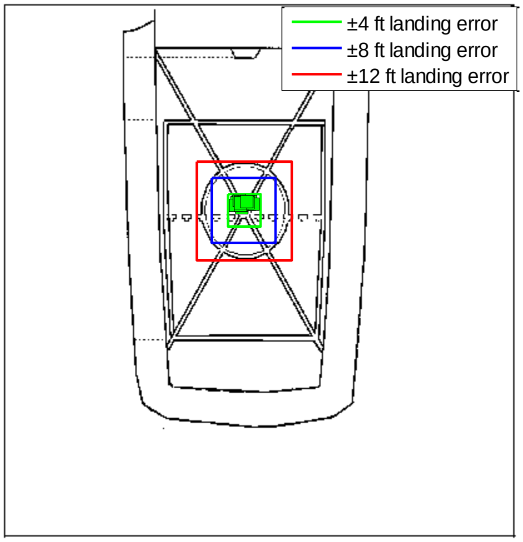


Figure 2. Approach Trajectory



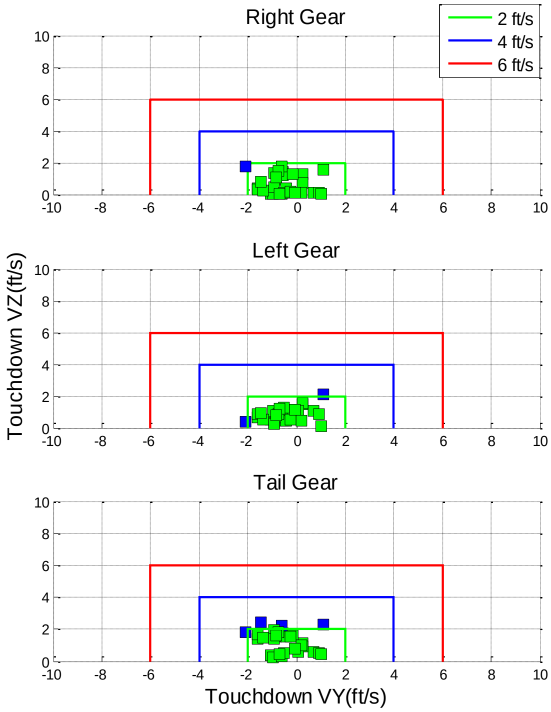


Figure 3. Landing Spot Scatter

Figure 4. Touchdown Speed Scatter

In the current period, we performed stability analysis of the closed-loop system using full-order linearized models of the medium class helicopter. The analysis model includes feedback of inner-loop (attitude control), outer-loop (translational rate control), and navigation loop (position control). The stability analysis used a SISO based stability margin analysis, i.e. by breaking the closed-loop system at each of the four axes independently at the actuator. We then obtain the open-loop system of the particular axis under investigation. By looking at the frequency characteristics of the open-loop system, we obtain the stability margins. The method and results are summarized in Figure 5 and Table 1. Figure 6 shows a sample of the roll-axis open loop transfer function. The results indicate relatively good stability margins with most axes exceeding the standard 45° / 6 dB requirements for phase and gain margin. Only the roll axis is on the 45° boundary. It is noted that lack of RPM dynamics results in optimistic margins for the heave and yaw axes.

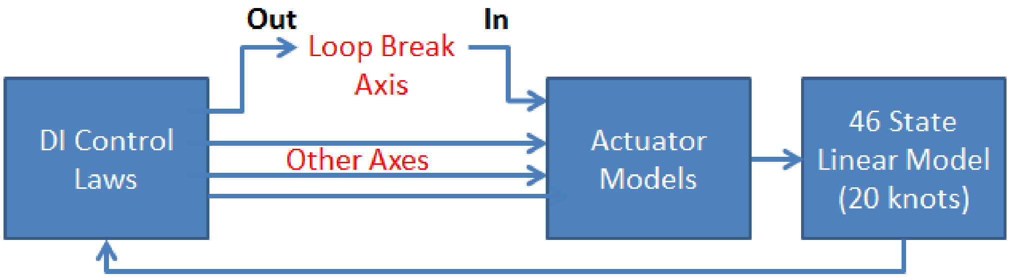
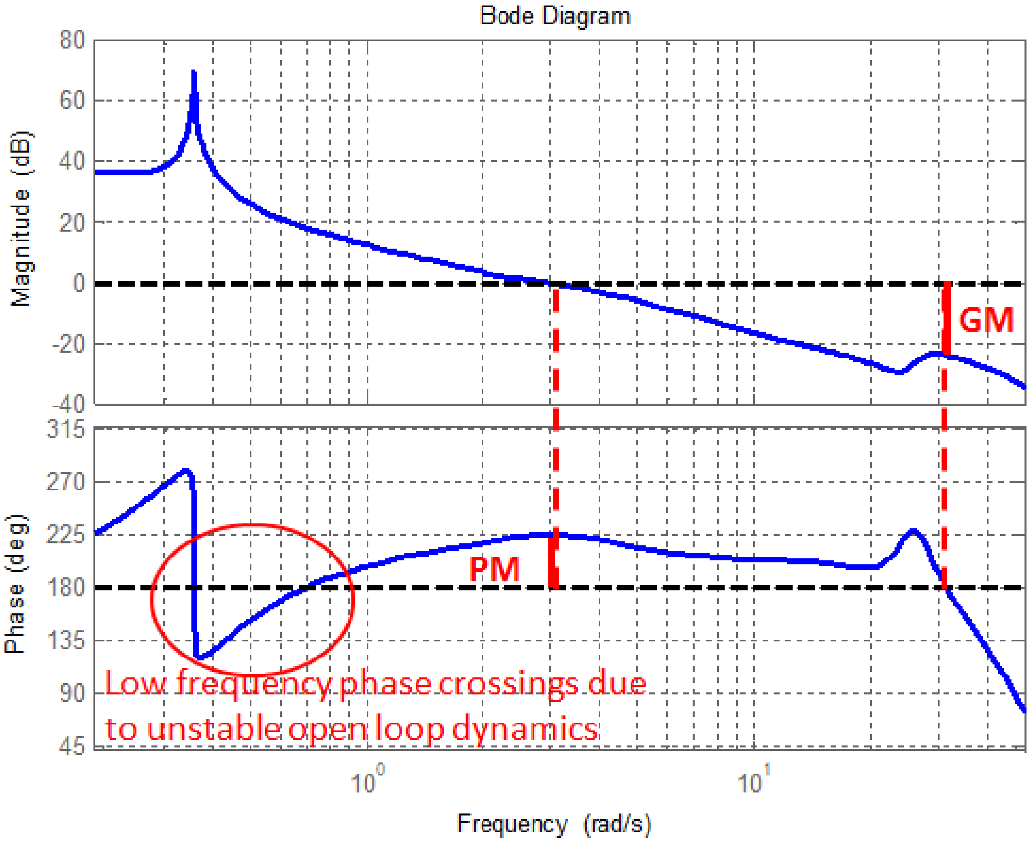


Figure 5. Open loop system generation

Axis	Gain Margin	Phase Margin	Gain Crossover
Roll	+24 dB / -18 dB	44.6°	2.8 rad/sec
Pitch	+ 15 dB / -15 dB	51°	4.4 rad/sec
Yaw*	+∞ dB/ -15 dB	74°	5.0 rad/sec
Heave*	+29 dB / -22 dB	52°	0.64 rad/sec

Table 1 Stability Margin of 4 Axes

***Yaw / Heave margins are probably optimistic due to constant RPM model and no structural modes**



Low frequency phase crossings due to unstable open loop dynamics

Figure 6. Roll Axis Open Loop Frequency Response

Task 5 – Deck Motion Prediction Algorithm

During this reporting period, efforts were made to enhance the MCA based ship motion forecasting algorithm. The baseline Minor Component Analysis predicts future deck state based on observed patterns in past data history by determining the directions of smallest variance in the distribution of measurement

$$R = \sum_{i=1}^{N} X_i X_i^T$$

Those directions correspond to directions of the eigenvectors of the covariance matrix with the smallest eigenvalues:

$$B = \begin{bmatrix} B_1 & B_2 \end{bmatrix} = \text{Ordered Eigenvectors of R}$$

Knowing the above information, MCA algorithm predicts future signal X_2 based on a longer history X_1 by :

$$X_{2i} \approx -\left(B_2^T B_2\right)^{-1} B_2^T B_1 X_{1i}$$

Thus MCA requires an effective eigenvalue analysis tool for real-time implementation.

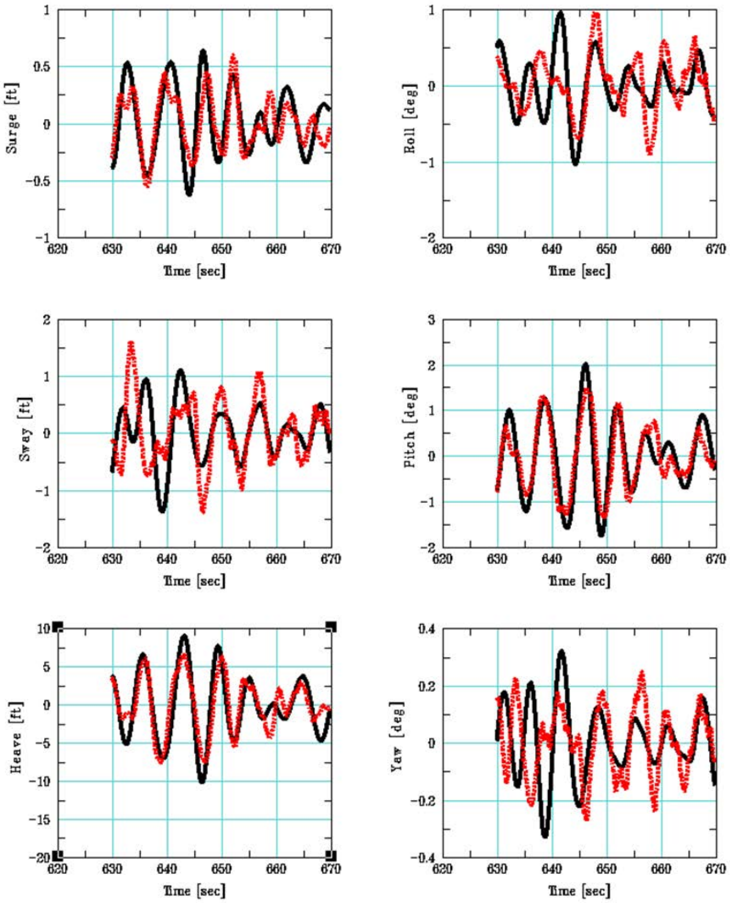


Figure 7. actual ship motion vs. predicted ship motion

Although the prediction horizon of the algorithm can be adjusted in real time during flight, the forecasting algorithm was developed to have an integer forecasting horizon. To accommodate dynamic forecasting time as required for shipboard landing from approach to touchdown, the MCA-based deck motion prediction algorithm with multiple prediction horizons (e.g., 1 sec, 2 sec, 3 sec, 4 sec, and 5 sec) has been developed to provide the continuous ship motion prediction by instancing multiple forecast modules. The predicted deck motion is then obtained for any desired prediction horizon using a linear interpolation with the multiple module outputs.

Task 6 – Path Optimization Algorithm

We are currently transferring the path optimization work to new personnel at NAVAIR 4.3.2.4 (as Co-PI John Tritschler has a new position at the U.S. Navy Test Pilot School). We are providing NAVAIR staff with code for the latest FLIGHTLAB models and controllers, as well as instruction, while Dr. Tritschler provides consultation on the use of the optimization tools.

3. Significance of Results

Both light class and medium class helicopter models are now integrated with the FLIGHTLAB simulation environment, allowing researchers to perform extensive simulation and analysis for further refinement of the concept, architecture and parameters of autonomous landing task.

Numerous simulation cases of approaching and landing validated the performance of the dynamic inversion control law for the medium amplitude SCONE case, which represents conditions not currently within the envelope of the H-60. Anticipated performance is obtained in the light class helicopter model with the same DI controller for approach, hover position tracking and landing. However, in the final stage of the approach we observed a significant amount of overshoot in X-position which may be due to larger effect of the airwake field on the light weight helicopter.

The updated ship motion prediction method provides better flexibility for landing control algorithms that make use of predicted deck states. We make use of this update in the coming quarter

4. Plans and upcoming events for next reporting period

Plant Model and Disturbance Models: The distribution of the heavy class (H-53 class) FLIGHTLAB flight dynamics models is expected to be accomplished next quarter. Additional ship motion cases will also be implemented. We also plan to develop some addition airwake cases (based on the SFS2 generic frigate shape) with winds from port and starboard. We also plan to involve high fidelity mathematical models of sensors and actuators to assess the overall stability of closed loop system.

Control Law Development: We will continue to develop novel control schemes for Task 8 *Station Keeping Control Laws* and Task 9 *Vertical Axis Control Laws*. The current control law partially realized these functions, we will continue to enhance control using deck motion prediction. The vertical axis control will address torque and control margin limit issues. ART will integrate the control laws as developed thus far for the generic heavy/medium/light weight class helicopters to provide our research team a consistent and unified model and analysis utilities to expedite further development. Configuration control is a challenge given the numerous members of the team at PSU, ART, NAVAIR, and NSWCCD.

Deck Motion Prediction: The MCA based ship motion forecast scheme will be improved to provide a better prediction for continuous forecasting time change. We will investigate the algorithm implementation to explore any potential improvement. ART will also process and integrate more SCONE ship motion data with the simulation model for further test and evaluation.

Path Optimization: In the next research period we will try to develop a spline-based reference trajectory generation algorithm to compare with current straight line reference path. Direct mathematical formulation of objective functions will be investigated to support fast optimization algorithms.

With the current path parameterization scheme, we will investigate different wind over deck cases and the light class simulation model. These will be good test cases to help train new personnel at NAVAIR who will be starting work on the project.

Control Parameter Optimization: The optimization scheme will be formulated, including the objective function and the constraints, in order to find the optimal gains of proposed control system. The optimization will be performed using a KS function-based optimizer which is available from FLIGHTLAB that supports simultaneous optimization of multi-objective functions. The parameters of command filter will also be considered for optimization. The resulting advanced control law with the optimal gains and filter parameters will be integrated into the flight dynamics model using CSGE in FLIGHTLAB.

5. References

6. Transitions/Impact

We continue to transition our models and control laws to counterparts at NAVAIR and NSWCCD (Sean Roark and Al Schwarz), and to John Tritschler (now at USNTPS).

7. Collaborations

Penn State and ART have collaborated directly with John Tritschler and Sean Roark at NAVAIR. In addition, we are communicating with other Navy researchers pursuing similar projects: Al Schwarz at NSWCCD and Dave Findlay at NAVAIR.

8. Personnel supported

Principal investigator:	Joseph F. Horn
Graduate Students:	Junfeng Yang, PhD Candidate

9. Publications

Horn J.F., Yang, J.F., He, C., Lee, D., and Tritschler, J.K. "Autonomous Ship Approach and Landing using a Dynamic Inversion Control with Deck Motion Prediction," 2015 European Rotorcraft Forum, Munich Germany, September 1-3, 2015.

10. Point of Contact in Navy

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Section II: Project Metrics

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November 13, 2015

1. Metrics

Number of faculty supported under this project during this reporting period: 1

Number of post-doctoral researchers supported under this project during this period: 0

Number of graduate students supported under this project during this reporting period: 1

Number of undergraduate students supported under this project during this period: 0

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: 0

Number of publications (all) during this reporting period: 1

Number of patents during this reporting period: 0

Number of M.S. students graduated during this reporting period: 0

Number of Ph.D. students graduated during this reporting period: 0

Awards received during this reporting period: 0

Invited talks given: 0

Conferences at which presentations were given (not including invited talks above): 1