THE FINAL PHASE OF A HELICOPTER AUTOMATIC LANDING ON A VESSEL'S DECK

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Abstract

The paper presents part of the results obtained in the HELIMARIS project ("Modification of an optionally piloted helicopter for maritime mission performance") led by PZL Swidnik in cooperation with Warsaw University of Technology and CTO. In the paper, way of integration of light helicopter dynamic model, automatic control and prediction algorithm for landing on the moving vessel at different sea states is presented. For the purpose of the landing task a Linear Quadratic Regulator (helicopter control) and autoregressive method with parameters calculated using Burg's method (vessel movement prediction) are used. The model of the helicopter is developed and evaluated in FLIGHTLAB software using flight test data for validation. Developed system for landing of the helicopter on the vessel is presented, results are shown and discussed.

1. INTRODUCTION

The objective of this research was to elaborate the methodology to perform final phase of helicopter automatic landing on a moving vessel's deck by integration of two subsystems dedicated for this task. An automatic control algorithm based on Linear Quadratic Regulator (LQR) methodology which is the part of Automatic Flight Control System (AFCS) is combined with algorithm predicting the future vessel movement. The prediction algorithm is based on autoregressive method with parameters calculated using Burg's method.

This paper is a further development of work presented in [1].

Integration of helicopter dynamic model, automatic control and prediction algorithm is shown. Tests cover automatic helicopter landing on the moving vessel's deck at two different sea states.

2. CONTROL METHOD

For automatic landing of the helicopter on a moving vessel, Linear Quadratic Regulator (LQR) methodology was used. This controller requires the linear model of the controlled object and information about all controlled state variables. It works in a feedback loop, using differences between actual and desired system state variables. Theoretical basis of the methods are presented in [1].

The LQR gains are calculated based on reduced helicopter dynamic linear model and then applied to the full nonlinear helicopter dynamic model. Linear model of the controlled helicopter was developed from the nonlinear model described in Chapter 4. For the final landing phase on the moving vessel's deck, it is assumed that twelve state variables (position, attitude, linear velocities, angular velocities) of the helicopter and the vessel are known and available for controller. It is assumed that this data is collected using onboard integrated INS/GPS systems (from the vessel data is transmitted to the helicopter using data link).

Operation of the LQR depends on selection of the weighting matrices values (Q – state weight matrix, R – control weight matrix). Here, selection of these values was made using iterative expert method till the answers of the helicopter model were adequate to fulfill the task of automatic landing on a moving confined vessel's deck.

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3. PREDICTION ALGORITHM

Prediction of the vessel movement is essential for safe and successful landing of the helicopter on it. Several research papers where published on this subject presenting various methodologies; for instance in [2] and [3] methodology of Landing Period Designator (LPD) is described based on energy index. Kalman filter techniques for estimation of vessel velocities, accelerations ad motions are presented in [4]. Artificial neural networks for predicting the vessel movements were used in [5]. Prediction of vessel attitude changes using the Minor Component Analysis (MCA) is presented in [6] and [7]. Interesting solution based on dynamic rollover risk prediction using statistical methods can be found in [8].

In this research the prediction of the vessel's movement is based on autoregressive method with model parameters calculated using Burg's method [9], working in a real time. Vessel's position and attitude prediction is a helicopter's subsystem. When approaching to the vessel, prediction system collects data for 120 seconds (each one second) and using autoregression algorithm estimates next 10 seconds of the vessel's deck position and attitude.

The autoregressive prediction model has a form:

(1) $x_{N+L} = -\sum_{i=1}^{N-1} a_i x_{N+L-i}$

where:

- N is the number of measured samples from the past,
- L is the current number of a predicted sample,
- a_i are the model (autoregressive) parameters calculated using Burg's method,
- x_{N+L-i} are samples which are used as an input to the autoregressive model from last N samples; the model is recursive – in the first step of the algorithm work only measured data are used (first N samples), in each next step also predicted samples from previous steps are included in the input of the algorithm (last N samples).

In Burg's method, model (autoregressive) parameters a_i for a selected autoregressive order are determined by minimizing the total sum of the square of the difference between original and forward linear prediction values and the square of the difference between original and backward linear prediction values.

4. HELICOPTER DYNAMIC MODEL

The helicopter dynamic model is developed in FLIGHTLAB software. Model used is based on PZL SW-4 helicopter configuration. It is a single rotor helicopter with one turboshaft engine, classic configuration. Main rotor is articulated, three-bladed. Tail rotor is two-bladed, see-saw. All elements of the helicopter, except the undercarriage, are modeled as rigid. The main and tail rotors are modeled in a similar way, using blade element approach with flapping dynamics included. The aerodynamic model selected is quasi-steady with stall delay, and Peters-He 6 state induced velocity model. The interaction between rotors and fuselage are also modeled. The aerodynamic loads of the fuselage and empennage are modeled using empirical look-up tables. The engine model is based on FLIGHTLAB turboshaft engine model with detailed model of its dynamics and control systems.

The helicopter numerical model is validated using flight test data delivered by the helicopter's manufacturer. The validation covers both steady flight and dynamic response cases.

Based on described nonlinear model, linear model was developed and used to establish LQR gains.

Coordinate systems used are described in [1].

5. VESSEL MODEL

The numerical model of the vessel motion was included in FLIGHTLAB software. The vessel fuselage is modeled as rigid 6-dof body. Its motion is described using several harmonics reflecting 6 degrees of freedom of the vessel motion. The wind model over vessel deck is calculated from a look-up table of steady winds for given sea-state, vessel speed and azimuth, and turbulent, stochastic components.

6. FINAL PHASE OF THE LANDING

Generally, procedure of a helicopter landing on a vessel's deck is composed of three phases – approach to a vessel, relative hover over a vessel's deck (hovering here means following a vessel's deck position) and final landing maneuver leading to touchdown. Here, last two phases are considered.

At these phases several conditions influence a helicopter behavior:

- vessel's deck position and attitude is changing in time,

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- area of the landing is confined,
- constant wind, wind gusts and turbulence can occur.

Despite environmental conditions automatic control has to be adapted to helicopter operation constraints:

- maximum touchdown velocity cannot be exceeded (here maximum touchdown velocity is 6.56 feet/s),
- maximum values of pitch and roll angles cannot be exceeded during touchdown due to the possibility of the sliding of the helicopter on the deck (here maximum values of pitch and roll angles are 10 degrees).

To fulfill the task of the landing on the vessel's deck, two subsystems are combined – LQR (autopilot here) is combined with autoregression algorithm (prediction system). Prediction system is used to analyze the vessel motion (position and attitude) and estimate the vessel motion in the future. It also gives information to the autopilot to start the final landing maneuver.

The phases of the integrated system work are:

- automatic hover over the landing deck at preselected safe height,
- estimation of the vessel's deck position and attitude by the prediction system – 10 seconds ahead prediction is assumed here,
- system analyze if estimated pitch and roll angles of the vessel deck do not exceed the assumed values at the prospective touchdown moment and if the vessel deck will not hit the helicopter skids in the time period when the landing maneuver is performed,
- helicopter start landing – it performs this maneuver in assumed period of time, which is the same as prediction time window,
- helicopter touches down.

7. TEST CASES

Test cases are performed to check:

- performance of the vessel's motion prediction system,
- performance of the integrated system in task of the automatic helicopter landing on a moving vessel's deck.

For the tests of prediction system performance, vessel model described in Chapter 5 was used. Position and attitude of the center point of the vessel's deck was predicted. Tests of the prediction system covered following cases:

- vessel was moving with constant forward velocity of 20 knots (33.75 feet/s),
- two sea states (Douglas sea scale) were analyzed – 3 and 5,
- one wave heading was considered - 180° (head waves).

Results of the prediction are shown in Figure 1 and Figure 2. Prediction of the vessel motion 10 seconds ahead is very good and seems to be sufficient to be used for automatic landing of the helicopter on the vessel's deck – difference between predicted and actual position in every case is less than 0.5 feet, difference between predicted and actual attitude in every case is less than 0.1 degree.

Second part of the tests was focused on the automatic landing of the helicopter on the vessel's deck, using integrated control system.

Tests of integrated system covered the same cases which were used for tests of prediction system. Results of the tests are shown in Figure 3 and Figure 4. In the figures helicopter responses are marked by black color and vessel responses are marked by red color. In the figures twelve helicopter state variables and four helicopter control variables are presented – X, Y, Z – position, PHI, THETA, PSI – attitude, Vx, Vy, Vz – linear velocities in body coordinate system, P, Q, R – angular velocities, main rotor swashplate pitch, roll and collective, tail rotor swashplate collective. Despite helicopter variables, six vessel state variables are presented – X, Y, Z – position, PHI, THETA, PSI – attitude. These vessel variables are essential to perform landing of the helicopter on the vessel – they are used as an input for autopilot.

Integrated control system managed to perform landing of the helicopter on the moving confined vessel's deck in both analyzed cases (landing is understood here as a first contact of the landing gear and the deck). In both cases landing was performed in assumed time window. Differences between position of vessel's deck center point and position of the helicopter touchdown were not more than 5 feet. In both cases, while touchdown, small (acceptable) differences between attitude of the helicopter and the vessel occurred. Touchdown velocity in both cases was less than maximum allowable touchdown velocity.

For the helicopter model maximum allowable control inputs values are:

- main rotor swashplate pitch (+5 : -5 [deg]),
- main rotor swashplate roll (+8 : -8 [deg]),

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- main rotor swashplate collective (+18.38 : 0 [deg]),
- tail rotor swashplate collective (+20 : -10 [deg]).

In both cases maximum control values were not achieved. Therefore, from control point of view operations are assumed to be safe.

8. CONCLUSIONS

In the paper, methodology of helicopter automatic landing on a moving vessel's deck is presented. For the purpose of realization of this task integrated control system was developed. It consists of automatic control algorithm (autopilot) and prediction algorithm used for estimation of the future vessel motion. Control algorithm is based on Linear Quadratic Regulator (LQR). Prediction system is based on autoregressive algorithm with parameters calculated using Burg's method. Integrated control system was applied to nonlinear helicopter model based on PZL SW-4 configuration, developed in FLIGHTLAB software.

Tests of the system performance covered separately tests of the prediction system and integrated control system for two sea state cases, using dedicated vessel model implemented in FLIGHTLAB software. Results of the tests confirmed rationale of using autoregressive method for vessel movement prediction and integrated control system for automatic helicopter landing on a moving vessel deck in degraded environmental conditions (wind gusts and turbulence).

9. ACKNOWLEDGMENTS

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10. REFERENCES

[1] Bibik P., Topczewski S., Żugaj M., „Development of an Automatic System for Helicopter Approach to a Moving Vessel," 44th European Rotorcraft Forum, Delft, Netherlands, 18-20 September 2018

[2] Ferrier B., Baitis A., Manning A., „Evolution of the Landing Period Designator (LPD) for Shipboard Air Operations," Naval Engineers Journal, July 2000

[3] Carico D., Ferrier B., „Evaluating Landing Aids to Support Helicopter/Ship Testing and Operations," 2006 IEEE Aerospace Conference, Big Sky, MT, 2006

[4] Triantafyllou M., Bodson M., Athans M., „Real time Estimation and Prediction of Ship Motions Using Kalman Filtering Techniques," MIT, July 1982

[5] Khan A., Bil C., Marion K., „Ship Motion Prediction for Launch and Recovery of Air Vehicles", Proceedings of OCEANS 2005 MTS/IEEE, Vol. 3., Washington, DC, 2005, pp. 2795-2801

[6] Zhao X., Xu R., Kwan C., „Ship-Motion Prediction: Algorithms and Simulation Results," 2004 IEEE International Conference on Acoustics, Speech, and Signal Processing, Montreal, Que., 2004

[7] Horn J., Yang J., He C., Dooyong L., Tritschler, J., „Autonomous Ship Approach and Landing Using Dynamic Inversion Control With Deck Motion Prediction", 41st European Rotorcraft Forum, Munich, Germany, September 2015

[8] Dang-Vu B., „Shipboard Landing Period Based on Dynamic Rollover Risk Prediction," 44th European Rotorcraft Forum, Delft, Netherlands, 18-20 September 2018

[9] Collomb C., „Burg's Method, Algorithm and Recursion", November 10, 2009

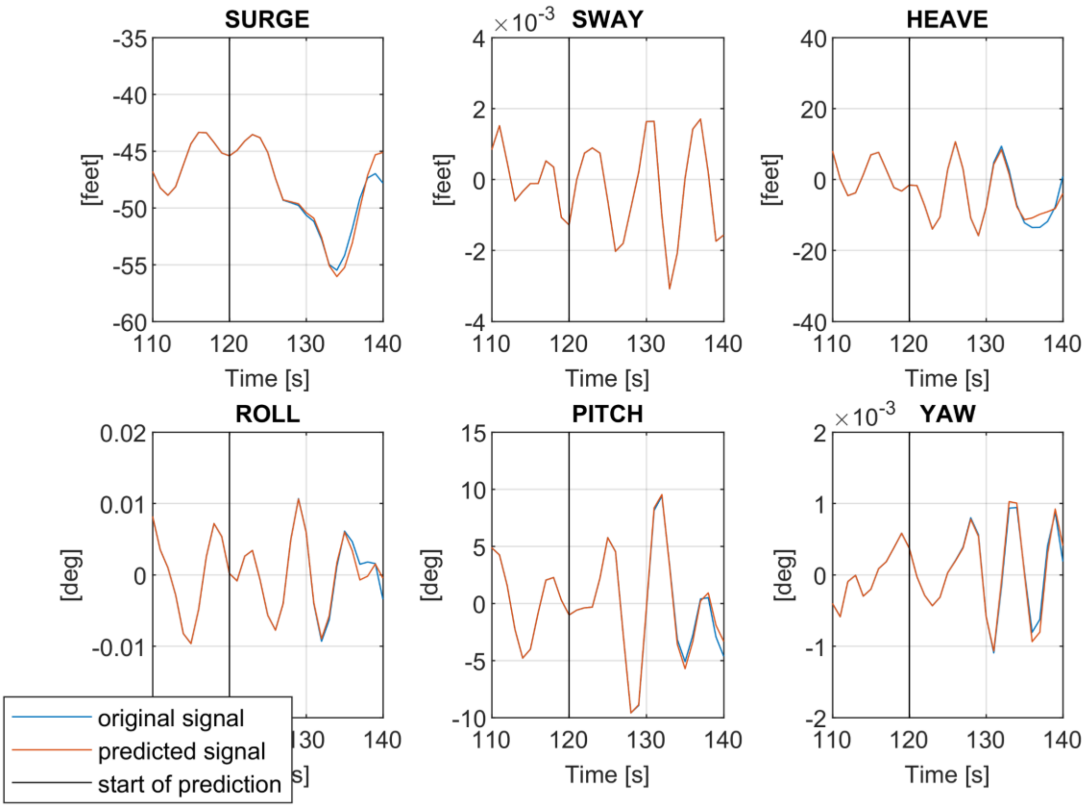

Figure 1 Prediction system performance – sea state 3

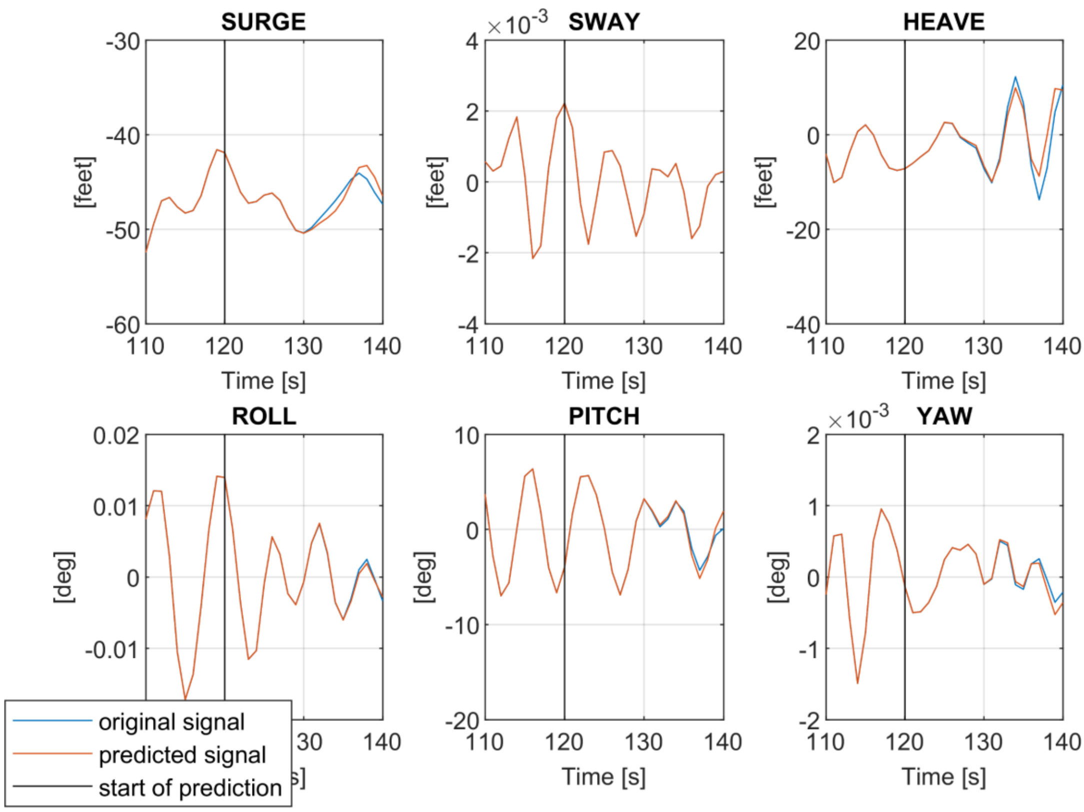

Figure 2 Prediction system performance – sea state 5

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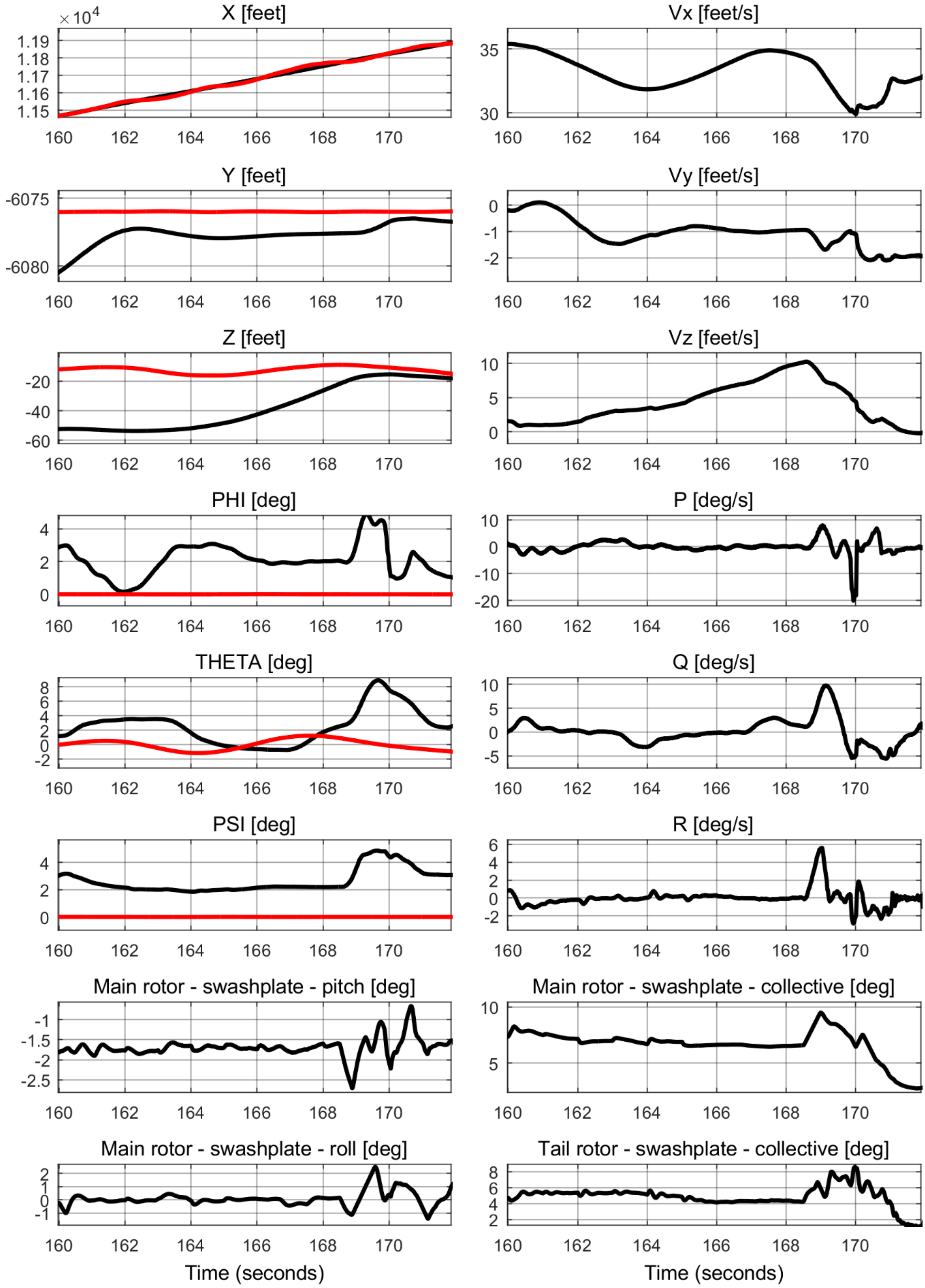

Figure 3 Integrated system performance – landing – sea state 3 (red – vessel, black – helicopter)

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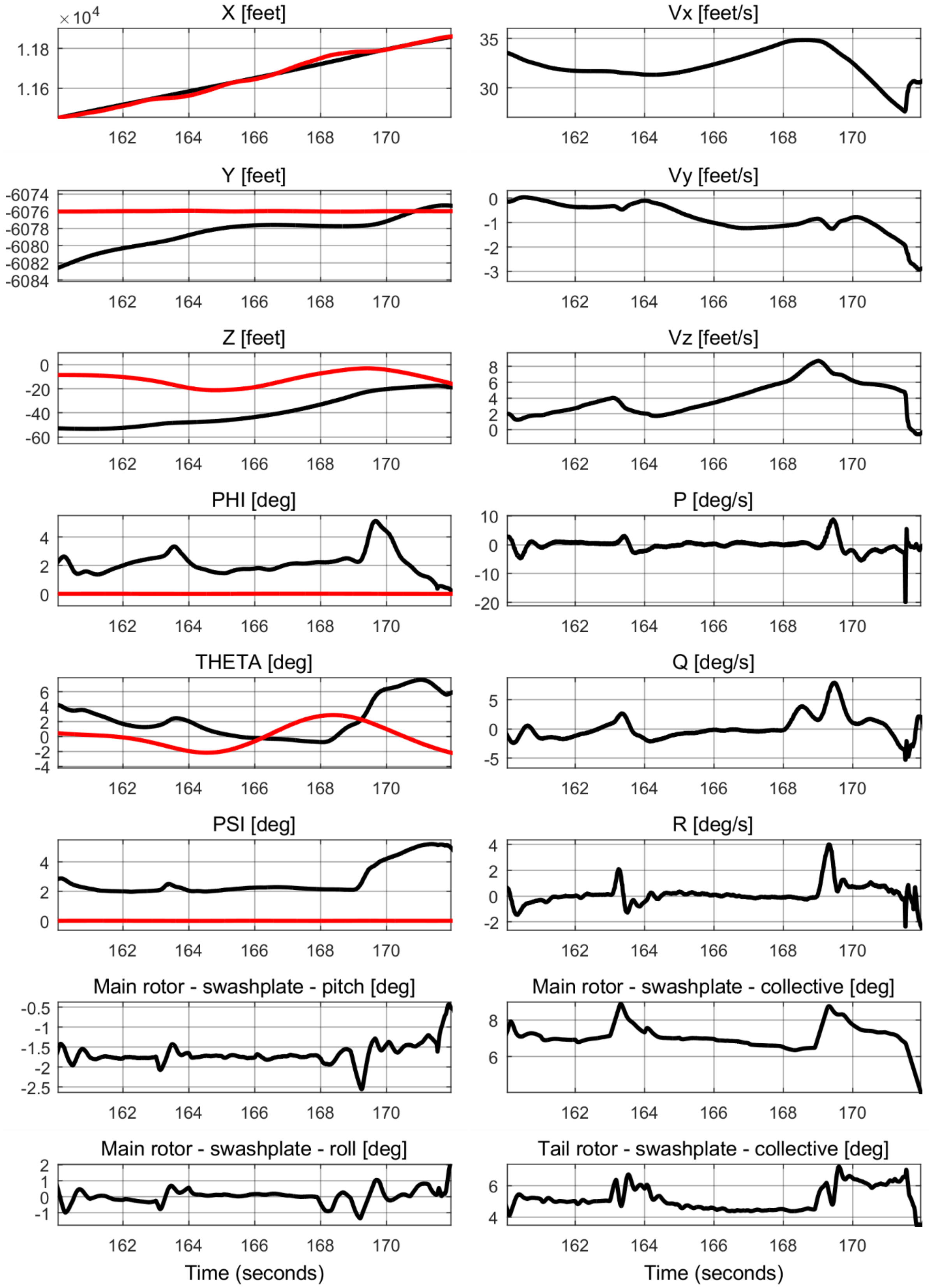

Figure 4 Integrated system performance – landing – sea state 5 (red – vessel, black – helicopter)

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