Flight Anomaly Detection for Airborne Wind Energy Systems

Salma, Volkan; Schmehl, Roland

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

PAPER • OPEN ACCESS

Flight Anomaly Detection for Airborne Wind Energy Systems

View the article online for updates and enhancements.
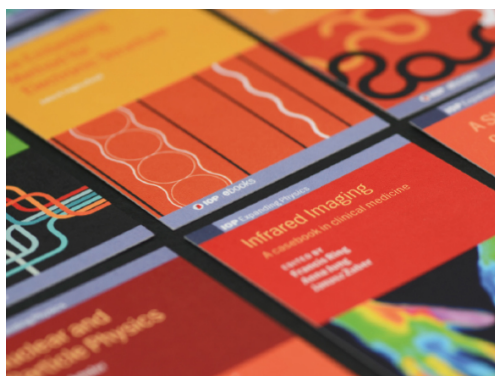
Flight Anomaly Detection for Airborne Wind Energy Systems

Volkan Salma and Roland Schmehl

Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

E-mail: `r.schmehl@tudelft.nl`

Abstract. Airborne wind energy (AWE) systems use tethered flying devices to harvest wind energy beyond the height range accessible to tower-based turbines. AWE systems can produce the electric energy with a lower cost by operating in high altitudes where the wind regime is more stable and stronger. For the commercialization of AWE, system reliability and safety have become crucially important. To reach required availability and safety levels, we adapted an fault detection, isolation and recovery (FDIR) architecture from space industry. This work focuses on, "flight anomaly detection" layer of the FDIR. Tests verifies that proposed architecture is capable of detecting flight anomalies without generating false alarms.

1. Introduction

Airborne wind energy (AWE) systems use tethered flying devices to harvest wind energy from higher altitudes, which are not accessible by conventional tower-based wind turbines. While the use of a tensile support structure greatly reduces the material effort and investment costs for energy generation, the use of a flying system component poses a major challenge on the control system, especially in the light of long-term operation in an unsteady turbulent wind environment [17]. Current AWE prototypes have reached power ratings of up to several hundred kilowatts and companies are aiming at long-term operation to be able to commercialize the products [8, 13]. Some representative examples are shown in Figure 1. For the successful
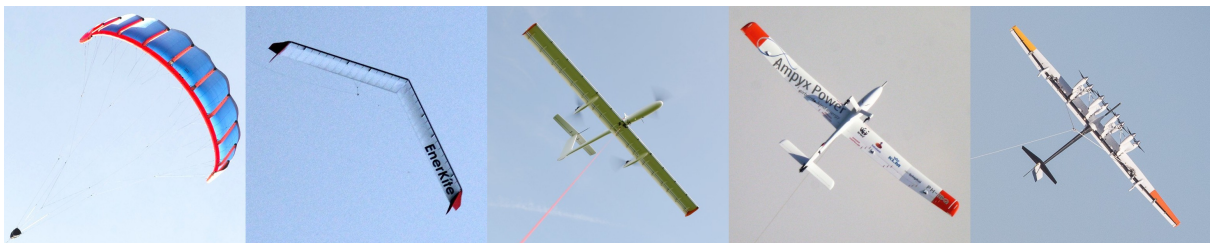

Figure 1. Selected AWE systems currently in development: Kitepower, EnerKíte, TwingTec, Ampyx Power and Makani Power (from left to right), generating up to 600 kW per single system.

commercialization, designing a reliable, operationally robust and safe AWE system has become one of the main engineering challenges in the field. Despite of the differences between the various

AWE concepts, the industry consensus is that safe and robust operation is necessary also for the public acceptance.

Improving the reliability and safety of a system requires active mitigation of identified risks. These efforts referred as system health management or conversely fault management in the literature. Even though there is no common methodology for health management among different application domains due to different fault characteristics and different recovery actions, following classification can be done according to fault detection approach [1]:

- Classical techniques
- Model based and parameter estimation methods
- Knowledge and rule based methods
- Machine learning based methods

In the conventional wind turbine domain, there are few literature reviews for the health management [7, 6, 2]. Lately there has been an increasing trend of using model based reasoning algorithms for fault detection. Acoustic emission has also gained more attention as a feature to detect incipient failures of the wind turbines [11].

For the space domain, efforts are on-going in NASA[4] and ESA to support the industry by providing guidelines for creating reusable and trustworthy health management systems. In space literature systematic health management architecture is called as fault detection, isolation and recovery (FDIR). As a result of the working groups, NASA published draft version of Fault Management Handbook [5]. Independently developed ESA FDIR guideline will be published soon.

Space missions need to perform their tasks with a high level of autonomy under extreme environmental conditions. In order to reach the similar robustness levels for AWE systems, we tailored a hierarchical FDIR architecture which is developed for European earth observation satellites [14].

After presenting the high level architecture of the tailored FDIR , this work will focus on the "flight anomaly detection" layer of the FDIR which consists of three decision engines. One for checking if the kite is still under control, second is to ensure that kinetic energy level of the airborne part is below a limit and the third engine is for confirming that position of the kite is still in the operation envelope. Validation tests with real flight data show that proposed system is capable of detecting critical flight anomalies without generating false alarms. We consider that the proposed flight anomaly detection system is an important contribution to the AWE literature for the commercialization and the certification processes.

2. Objectives

This study proposes an FDIR approach for airborne wind energy systems to reach the commercially required reliability and safety levels. In practice FDIR requirements are derived from the safety analyses of the systems [10]. As a case study, safety analyses for the flexible-wing kite power system of Delft University of Technology and Kitepower B.V is presented in [15]. This research elaborates the implementation and validation of proposed FDIR architecture in [15].

The first three layers of the proposed FDIR are to increase the availability and robustness of the system. We targeted a failure rate of 100×10^{-6} failure/hours for the first commercial product. The safety design target of FDIR is to prevent the catastrophic failure scenarios which are spotted by FTA (Fault tree analysis) and FMEA (Failure mode and effect analysis) [15].

3. Methodology

We adapted the FDIR architecture from space industry [14], which has five hierarchical levels, as illustrated in Figure 2.

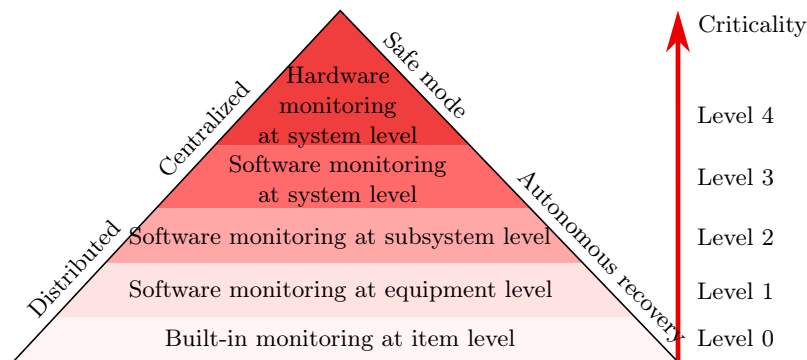The five FDIR levels work as the following:

Figure 2. Hierarchical fault detection, isolation, and recovery [15]

- Level 0 performs item level built-in monitoring. Some external units are capable of recovering autonomously from faults without affecting the performance of the system. Software and hardware watchdogs embedded in the sensors are typical examples for Level 0 FDIR.

- Level 1 monitors the system at equipment level for units that cannot detect and recover autonomously from faults. Using the redundant sensor instead of faulty one is an example of Level 1 FDIR.

- Level 2 checks the performance at subsystem level. The output voltage reading from the on-board power subsystem and resetting the subsystem in case of a fault is an example of Level 2 FDIR.

- Level 3 monitors the system level performance. One or more faults, which could not be recovered at Level 0, Level1 or Level2, are caught by the Level 3 FDIR with a holistic flight anomaly detection system.

- Level 4 performs hardware-only monitoring at system level to protect the system from catastrophic events. One example for Level 4 FDIR is cutting of the tether for an emergency landing in the event of critical flight anomaly.

FDIR Level 3 and FDIR Level 4 run completely independent from the flight software, because these layers affect the system safety factor directly. Sensors to be used for theory anomaly detection have to be trustworthy. As inputs, angular and linear acceleration measurements, position data and steering motor command are considered sufficient for the proposed system.

In the kite power system, there are more than one accelerometer for redundancy purposes. The anomaly detection system uses the same consolidated acceleration data which the flight control system uses. Recovery of critical sensor data loss is handled in the lower levels of FDIR, if the recovery of the critical sensor was not possible then flight anomaly alarm is triggered to terminate the flight.

Low false alarm rates are critically important for FDIR Level 3 and Level 4, because false positive alarms may decrease the availability of the system with triggering emergency landing when it is not necessary. On the other hand, false negatives may cause hazardous consequences in case the FDIR system does not command for emergency landing when it has to.

Three main criteria have been defined to decide whether the operation is still safe during the flight. These are; (i) Kite shall be under control, (ii) kinetic energy of the kite shall not exceed a predefined limit (iii) and the position of the kite shall be in the allowed operation zone.

A violation of any of the above-mentioned criteria is sufficient for triggering the anomaly detection alarm. A time-triggered filter is used to filter out false alarms. Thus, the violation should last at least one second to raise the anomaly flag. The high-level architecture of the flight anomaly detection system is shown in Figure 3.
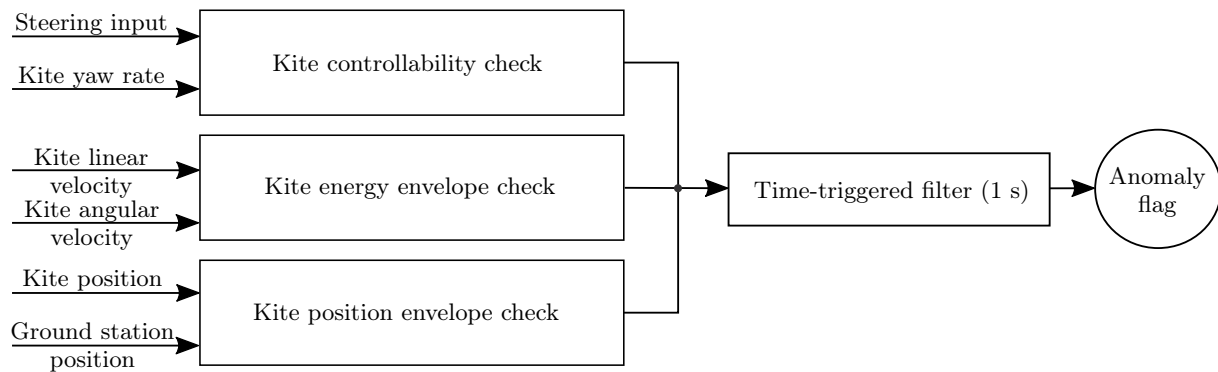
Figure 3. High-level architecture of the kite anomaly detection system.

(i) **Kite controllability:**
Steering, altitude and the attitude of the kite need to be controllable at any moment under any environmental condition. An independent system is considered necessary to check if the flight control system is able to control the system as expected. To check the controllability, we propose a fuzzy logic expert system using a Mamdani fuzzy inference engine[12] for steering anomaly detection. Mamdani systems incorporate expert knowledge in the form of IF-THEN rules expressed in natural language. Proposed fuzzy engine uses the steering motor command and yaw-rate response of the kite to decide whether the kite is still under control. The positive correlation between the steering input and the yaw-rate measurement is presented in [9].

Five triangular membership functions defined both for the steering and yaw rate inputs. These inputs called as "negative high", "negative medium", "low", "positive medium" and "positive high". Membership function against to the input values are defined as shown in the Figure 4 and Figure 5.
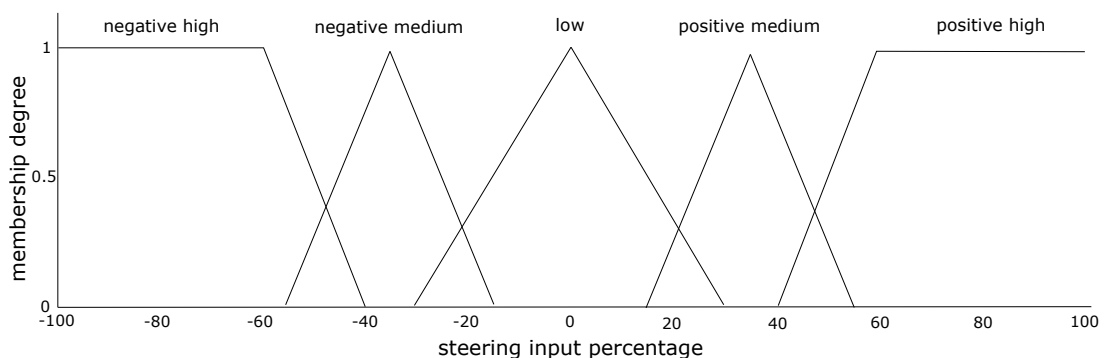
Figure 4. Membership functions for the fuzzification of steering input

As detailed in [9], correlation given in the Equation 1 was found using system identification methods. While C_1 and C_2 are being kite specific parameters dependent on mass, geometry and power setting, the term $\mathbf{g} \cdot \mathbf{y}_{(K)}$ relates to the angle between the gravity vector and the $y_{(K)}$ axis.

$$r_K = C_1 v_a^n u_S + C_2 \frac{\mathbf{g} \cdot \mathbf{y}_{(K)}}{g} \tag{1}$$

Figure 5. Membership functions for the fuzzification of yaw-rate measurement

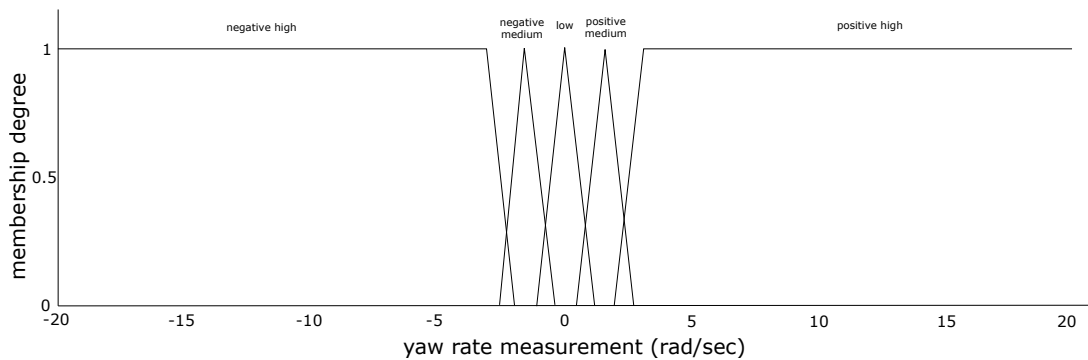| IF (steering command)	AND (yaw rate measurement)	THEN: (anomaly result)
negative high	negative high	normal
negative high	low	anomaly
negative high	positive high	anomaly
negative high	negative medium	warning
negative high	positive medium	anomaly
negative medium	negative high	warning
negative medium	low	warning
negative medium	positive high	anomaly
negative medium	negative medium	normal
negative medium	positive medium	anomaly
low	negative high	anomaly
low	low	normal
low	positive high	anomaly
low	negative medium	warning
low	positive medium	warning
positive medium	negative high	anomaly
positive medium	low	warning
positive medium	positive high	warning
positive medium	negative medium	anomaly
positive medium	positive medium	normal
positive high	negative high	anomaly
positive high	low	anomaly
positive high	positive high	normal
positive high	negative medium	anomaly
positive high	positive medium	warning

Table 1. Mamdani fuzzy interference engine rules between the inputs and outputs

Considering the correlation between steering input and corresponding yaw rate response, fuzzy relationship shown in Table 1 are defined between the input variables and the output variable "steeringAnomalyDegree":

The defuzzification of the "steeringAnomalyDegree", to acquire the real anomaly value, is implemented with the membership function shown in Figure 6.
Anomaly degree values of 0.8 or greater is set as alarm triggering condition flight anomaly.
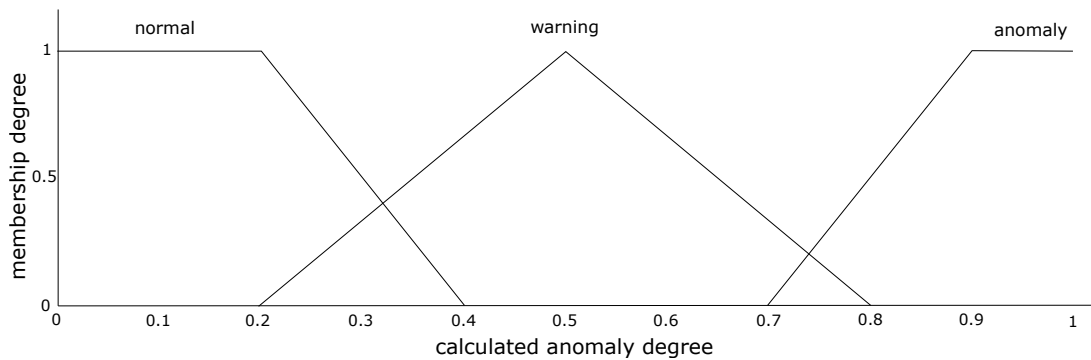
Figure 6. Membership functions for the defuzzification of anomaly degree output

(ii) **Safe position envelope:**
Tether length limits the operation volume of the kite. To have a safe operation, kite always needs to be connected to the ground. In case of tether rapture kite can fly away and may cause catastrophic consequences[5]. Position control to ensure that kite is always in the operation zone is implemented to mitigate the risk of catastrophic events.

(iii) **Safe energy envelope:**
If the kite is "out of control" possible damage level is directly proportional to kinetic energy of the kite. Therefore, in order to operate safely, kite shall have an energy level which is below a predefined threshold level. If total kinetic energy exceeds the limit immediate actions needs to be taken. Equation 2 shows that total kinetic energy kept by the kite is the sum of the rotational and the translational kinetic energy. For the rotational kinetic energy calculation, a constant inertia tensor ($\mathbf{I}$) for the kite system is presumed.

$$E_{Kt} = \frac{1}{2}mv^2$$
$$E_{Kr} = \frac{1}{2}\omega^T \cdot I \cdot \omega$$
$$E_K = E_{Kt} + E_{Kr} \tag{2}$$

4. Results

Calibration and validation of the proposed anomaly detection system with the real flight data are still ongoing. At the time study, system is tested with five flight logs with a total flight time of approximately 14 hours. System is designed to work only in power generation mode. Since the mode of operation data was not recorded in the flight logs, only the data which kite has an altitude of 100 meters or above considered valid. When the kite altitude is below 100 meters, it is considered that kite is either on ground or in take-off/landing mode so the anomaly detection is not enabled.

Two of the five flight logs are selected from nominal flights. Other three test flight logs have stall events. Stall event cases are selected to verify the fuzzy logic engine which is developed for checking the kite controllability criteria. Meaningful results for two nominal flights and stall events are similar. Therefore only one of the nominal flight case and one of the non-nominal flight case will be presented in this paper.

Simulation time stamp (ms)	Steering input [-100,100]	Yaw rate (rad/sec)	Anomaly degree [0,1]
4402.92	65.13	0	0.8943
4403.02	64.22	0	0.8943
4480.42	64.98	0	0.8943
4480.52	64.00	0	0.8943
3833.83	-65.82	5.1816e-07	0.8943
1331.37	-64.00	-1.9129e-05	0.8943
1331.47	64.00	-1.9129e-05	0.8943

Table 2. Highest anomaly scores in the nominal flight which are filtered out by time trigger filter

4.1. Results for nominal flight conducted on 2019.11.29:
4.1.1. Kite Controllability: Anomaly detection system is fed with recorded original flight data. System wide anomaly detection is never triggered for the given nominal flight test case. Output of the fuzzy engine exceeded the predefined threshold value(0.8) 12 times in the total 3 hours and 17 minutes of flight time. However these overshoots never lasted more than 1 second. Consequently, values over the thresholds considered false alarms and filtered out by the time trigger filter which was set to one second. Table 2 shows eliminated false alarms which have the highest anomaly scores. It is assessed that unexpected high anomaly scores were because of the latency between the steering input and its corresponding yaw-rate feedback.

Histogram of the fuzzy engine output values for the conducted nominal flight is shown in Figure 7.
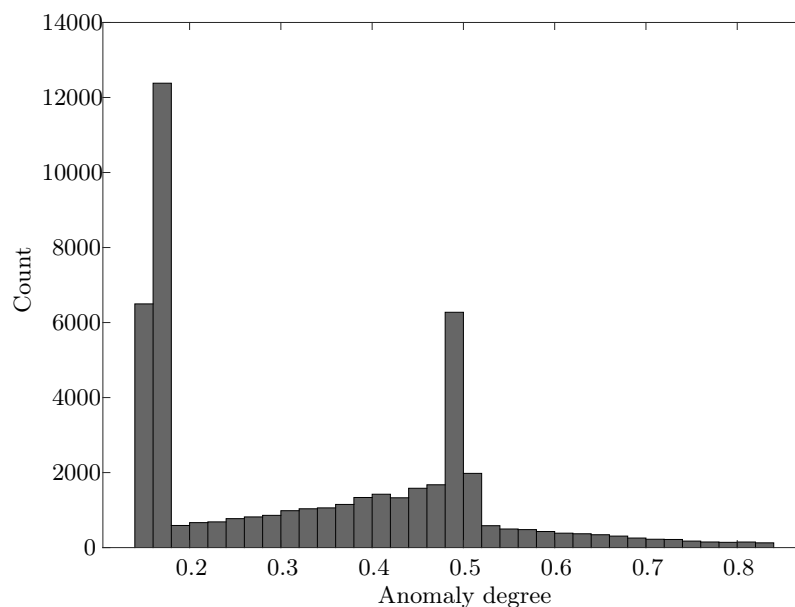

Figure 7. Anomaly degree level distribution for a nominal flight case

4.1.2. Energy Envelope: Maximum allowed kinetic energy is set to 100 kJ considering the potential damage impact of a AWES for the worst case scenario[16][15] and the energy based airworthiness categorization for civil unmanned aircraft systems proposed in [3].

	Maximum observed value (kJ)
Transitional kinetic energy	46.18
Rotational kinetic energy	1.25

Table 3. Maximum observed kinetic energy levels for nominal flight case

Table 3 shows the observed maximum levels of translational and rotational kinetic energy. Total energy level even in worst case is still in the allowed range with a tolerance of 52 percent. It is also observed that even with a cautious inertia tensor assumption, rotational kinetic energy is negligible comparing to translational kinetic energy in the nominal flight case.

4.1.3. Position Envelope: Considering only the data which kite has an altitude of 100 meters or above, calculated kite distance to the ground station varies between 362 meters and 201 meters. Given that maximum allowed distance set to 495 meters, considering 450 meters of tether length and 10 percent measurement error tolerance, kite was always in the safe operation zone. Thus, anomaly alarm because of position envelope violation is never triggered.

4.2. Results for non-nominal flight conducted on 2019.09.03:

4.2.1. Kite Controllability: According to the flight logs, which is written by the test team, an unexpected flight anomaly occurred. Later investigations shows that this was due to testing new power parameters in the control system. Operator reported that kite was almost going to front stall but it managed to recover itself after causing an overshooting of the tether. Figure 8 shows the steering command input, corresponding yaw rate response and simulated output of the kite controllability check during the anomaly. In total, control loss alarm triggered three times which all alarms last longer than 1 second. Thus, these 3 alarms indeed passes the time trigger filter and generates system wide anomaly alarm to take the emergency actions. As seen in the graphic first alarm lasted about 5 seconds. And the second detection lasted about 7 seconds and the final one lasted about 15 seconds until the system recovered itself.

19 seconds after the recovery, kite goes to front stall again which finally triggers the existing safety release mechanism for the smooth landing of the kite. Figure 9 shows the data of the second stall case. As expected controllability anomaly detection system simulation triggered many times all longer than one second which is sufficient to enable the system wide anomaly actions.

4.2.2. Energy Envelope: Rotational and translational energy levels are shown in Figure 10. Since total energy level is below allowed kinetic energy threshold(100K Joule), anomaly alarm because of kinetic energy envelope violation is never triggered.

4.2.3. Position Envelope: Kite distance to the ground station varies between 128 and 344 meters. No anomaly alarm triggered because of the violation of position envelope.

5. Conclusions

Due to the emerging interest in Airborne wind energy (AWE), a considerable number of prototype installations is approaching the stage of commercial development. As consequence, operational safety and system reliability are becoming crucially important. AWE systems are operationally more complex than conventional wind turbines. Therefore, a systematic safety engineering approach is necessary to reach the required safety and reliability levels. In this work, we have presented a multi-layered fault detection, isolation and recovery (FDIR) architecture. First results of the flight anomaly detection layer of FDIR have been presented in this work. To our
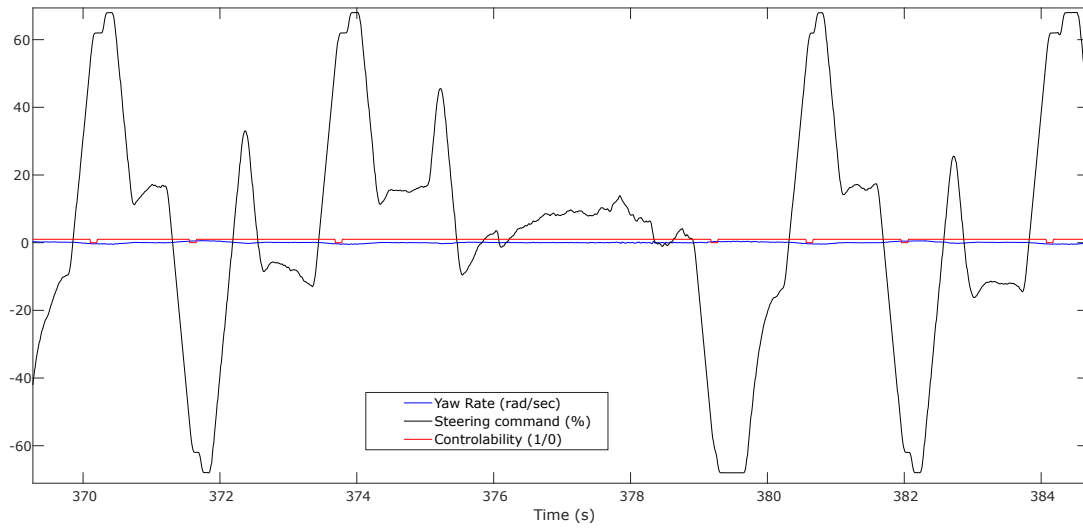
Figure 8. Steering input command (%), yaw-rate response (rad/sec) and simulated controllability anomaly result (1/0) during the first stall case
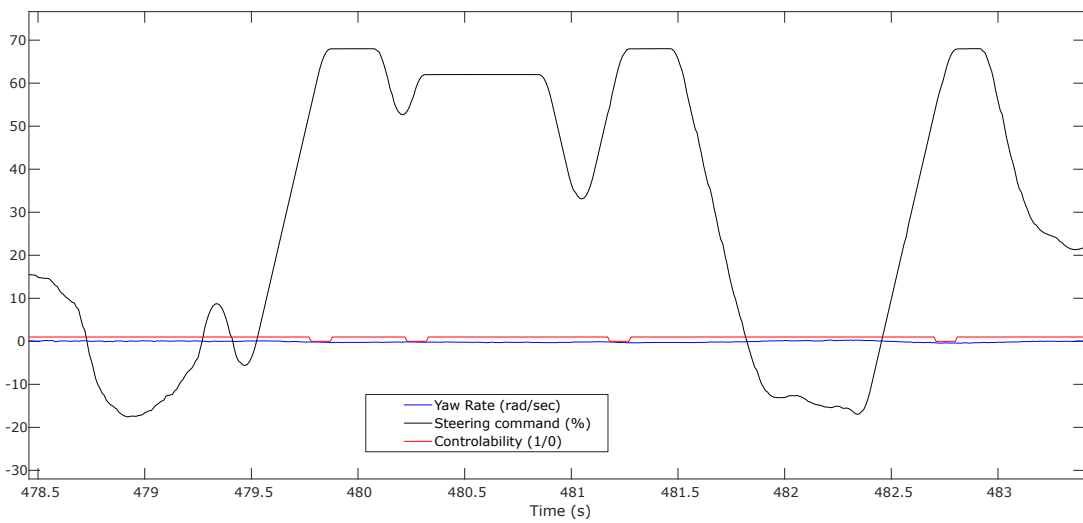

Figure 9. Steering input command (%), yaw-rate response (rad/sec) and simulated controllability anomaly result (1/0) during the second stall case

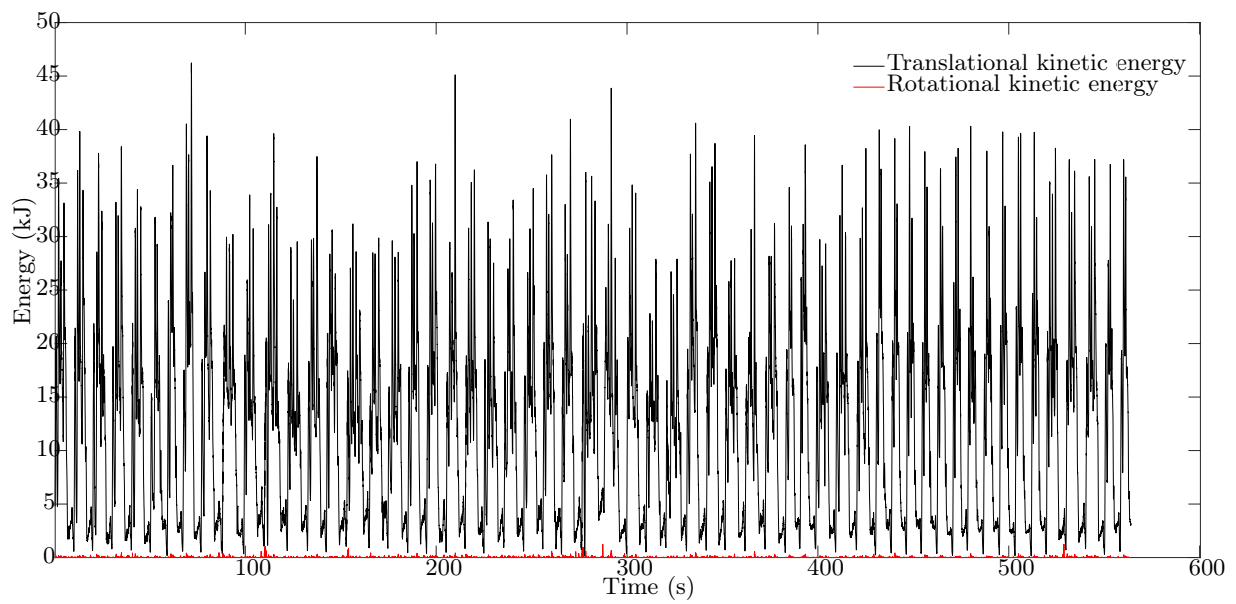knowledge, this is the first published study defining a systematic FDIR architecture for AWE systems.

Figure 10. Rotational and translational kinetic energy levels for the non-nominal flight case

Acknowledgments

References

[1] Pouliezos A.D. and Stavrakakis George S. *Real Time Fault Monitoring of Industrial Processes*. Springer, 2013.

[2] Yassine Amirat, Mohamed EH Benbouzid, Bachir Bensaker, and René Wamkeue. Condition monitoring and ault diagnosis in wind energy conversion systems: a review. In *2007 IEEE International Electric Machines & Drives Conference*, volume 2, pages 1434–1439. IEEE, 2007.

[3] R.A. Clothier, J.L. Palmer, R.A. Walker, and N.L. Fulton. Definition of airworthiness categories for civil unmanned aircraft systems (UAS). In *Proceedings of The 27th International Congress of the Aeronautical Sciences (ICAS 2010)*, Nice, France, 2010.

[4] Cornelius J Dennehy and Lorraine M Fesq. The development of nasa's fault management handbook. *IFAC Proceedings Volumes*, 45(20):295–300, 2012.

[5] Ryschkewitsch M. G. *National Aeronautics and Space Administration, Fault Management Handbook*. NASA, 2012.

[6] Z Hameed, YS Hong, YM Cho, SH Ahn, and CK Song. Condition monitoring and fault detection of wind turbines and related algorithms: A review. *Renewable and Sustainable energy reviews*, 13(1):1–39, 2009.

[7] RW Hyers, JG McGowan, KL Sullivan, JF Manwell, and BC Syrett. Condition monitoring and prognosis of utility scale wind turbines. *Energy materials*, 1(3):187–203, 2006.

[8] P. Jamieson. *Innovation in Wind Turbine Design*. John Wiley & Sons, Hoboken, NJ, 2 edition, 2018.

[9] C. Jehle and R. Schmehl. Applied tracking control for kite power systems. *Journal of Guidance, Control, and Dynamics*, 37(4):1211–1222, 2014.

[10] David M Johnson. A review of fault management techniques used in safety-critical avionic systems. *Progress in Aerospace Sciences*, 32(5):415–431, 1996.

[11] B. Lu, Y. Li, X. Wu, and Z. Yang. A review of recent advances in wind turbine condition monitoring and fault diagnosis. In *2009 IEEE Power Electronics and Machines in Wind Applications*, pages 1–7, 2009.

[12] Ebrahim H Mamdani and Sedrak Assilian. An experiment in linguistic synthesis with a fuzzy logic controller. In *Readings in Fuzzy Sets for Intelligent Systems*, pages 283–289. Elsevier, 1993.

[13] V. Nelson. *Innovative Wind Turbines: An Illustrated Guidebook*. CRC Press, Boca Raton, FL, 2019.

[14] X. Olive. FDI(R) for satellites: How to deal with high availability and robustness in the space domain. *International Journal of Applied Mathematics and Computer Science*, 22(1):99–107, 2012.

[15] V. Salma, F. Friedl, and R. Schmehl. Improving reliability and safety of airborne wind energy systems. *Wind Energy*, 23(2):340–356, 2020.

[16] V. Salma, R. Ruiterkamp, M. Kruijff, M.M.R. van Paassen, and R. Schmehl. Current and expected airspace regulations for airborne wind energy systems. In R. Schmehl, editor, *Airborne Wind Energy – Advances in Technology Development and Research*, Green Energy and Technology, chapter 29, pages 703–725. Springer, Singapore, 2018.

[17] R. Schmehl. Airborne wind energy - an introduction to an emerging technology. http://www.awesco.eu/awe-explained, 2019. Accessed 18 June 2020.