Testing and Evaluation of Radio Frequency Immunity of Unmanned Aerial Vehicles For Bridge Inspection

Edward Mahama, Thisara Walpita, Ali Karimoddini, Abdullah Eroglu, Navid Goudarzi, Tara Cavalline

Abstract—**Recent technological advances have led to an increase in the adoption of Unmanned Aerial Vehicles (UAVs) in a variety of use-case scenarios. In particular, Departments of Transportation in several states in the United States have been exploring the use of UAVs for bridge and infrastructure inspections to improve safety and reduce the costs of the inspection process. UAVs are remotely piloted from a cockpit or a ground station via radio channels. The UAV's state information and payload information are also transmitted to the cockpit/ground station via radio frequency (RF) signals. The RF channels that are commonly used by most UAVs are 72-73, 902-928 and 2400-2483.5 MHz bands, which is also shared by several other communication protocols such as, WiFi and ZigBee networks, and therefore, the interference effects with the other services on the UAVs operation performance cannot be overlooked, particularly due to the unstructured environments around bridges. Conventional Electromagnetic Compatibility (EMC) adherence requirements imposed on electronic systems are not adequate for UAVs due to their airborne nature and the presence of the other RF sources in the environment. Thus, in this work, we investigate the compliance of EMC requirements by designing and conducting field experiments to expose the UAVs to electromagnetic interference and distortions that are likely to be encountered during the UAV operation. The results of this work will enable us to assess the level of RF immunity of the general-purpose UAVs to aid in the selection of a suitable platform for bridge inspection and develop safety procedures for minimizing the impact of RF interference.**

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1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are receiving increasing attention for their use in a variety of applications, such as, remote sensing [1], search and rescue missions [2], disaster management [3], courier services [4], security and surveillance [5], wireless coverage [6], [7], precision agriculture [8], and infrastructure inspection [9]. Bridge infrastructure inspection is one of the application areas that is being explored by Departments of Transportation in several states across the United States to reduce the costs and improve the safety during the inspection process [10]. UAVs are remotely piloted with the command and control signals, and the telemetry data as well the payload data is transmitted via Radio Frequency channels (RF) [11]. The frequencies used by the command and control links of UAVs are typically in 72-73, 902-928 and 2400-2483.5 MHz bands [12], while the video transmissions are usually via on 5.2 GHz bands [13]. These frequencies are not used solely by the UAVs. There is a proliferation of services that use communication networks such as, WiFi, ZigBee, LTE, and GSM that operate on the same frequency bands. Therefore, there is a high chance for these services to impact the performance of UAVs particularly in the unstructured environment where there is a proliferation of RF sources [14].

Federal Communication Commission (FCC) requires all electronic equipment including UAVs to meet the minimum Electromagnetic Compatibility (EMC) to reduce the RF interference, but this may not be sufficient for deploying UAVs which are very much relying on continuous remote signals from a base station. Further, UAVs are usually manufactured for general-purpose use which is always governed by a trade-off between the performance and cost-effectiveness, and therefore, it is unlikely that the manufactures will be able to handle all environmental conditions and also maintain the EMC for all possible RF scenarios that a UAV may encounter during its operation.

To address these challenges, in this work, we investigate the UAV's immunity to interference by designing and conducting the field experiments that subject the UAVs to controlled electromagnetic interference and distortions that are usually encountered in a UAV-enabled bridge inspection environment. To achieve this goal, the subject UAV platforms are exposed to different levels of interference. It is followed by an analysis of how the presence of interference impacts the UAV's response to the cockpit's control commands. Finally, the impact of the RF stress on the transmission of telemetry data and payload (i.e camera) data from the UAV to the cockpit is investigated. The results of this experimental study provide recommendations for selecting appropriate UAV platforms in bridge inspection applications based on the conditions that may be encountered in a particular inspection scenario. Furthermore, our procedure for designing experiments for evaluating the RF immunity can be applied to many other applications of autonomous vehicles which are vulnerable to RF interference.

The remaining sections of this work are organized as follows; Section 2 provides the background and review of related works on interference immunity testing of UAVs. This is followed by a description of the experimental design in Section 3 where the test equipment, experimental setup, UAV platforms and frequency bands of interest are discussed. The results and discussion of the conducted experiments are presented in Sections 4 and 5, respectively. Finally, Section 6 concludes the paper and provides key observations, limitations, and

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future directions of the work.

2. Related Works

There are very few investigations available about the impact of electromagnetic interference on the operation of UAVs. In [12], a quantitative assessment was carried out to assess interference levels that the UAV's command and control links may be subjected to from licensed and unlicensed emitters. They concluded that RF interference may impact the reliability of UAV's command and control especially in the populated areas. In [15], RF assessment was conducted to characterize the RF environments at altitude up to 400 ft to develop a better understanding of interference impacts on small unmanned aircraft's command and control links. In this work, an RF sensing device was mounted on DJI S1000 drones that were then flown at various locations and altitudes to measure RF signals in frequency bands of interest. They also looked into the impacts of electromagnetic interference from the UAV's rotor on its functionality and observed that rotors have no interference impact on the UAV's operation. This work was performed as part of NASA's Unmanned Aircraft System Traffic Management Project.

The work in [16] carried RF immunity tests under a high electromagnetic field strength in an anechoic chamber to assess the reliability of the operation of a general-purpose UAV. Their work was motivated by the need to use UAVs to perform field experiments in locations close to high-power radio broadcasting stations. This work concluded that UAV can be reliably controlled even when subjected to strong electromagnetic fields. They, however, reported a potential loss of GPS signal in the 1.2-2.7 GHz frequency range. The RF interference immunity test in this work was performed with a customized UAV platform and therefore extensive testing with other general-purpose UAVs is needed to validate their results.

As part of French-German UAV-Assisted Ad Hoc Networks for Crisis Management and Hostile Environment Sensing (ANCHORS) project, the authors in [17] looked at the issue of RF immunity of the ANCHORS unmanned aerial system in a case study of an inland port environment. As such, they complemented the electromagnetic compatibility requirements of the electronic manufacturers that are expected to be adhered to by a set of RF frequencies that are likely to be encountered in the project test scenario. The finding of this work indicated that the UAV operated reliably at field strength of 30 Vm^{-1} with no malfunctions. However, they indicated that the experiments in different case scenarios and other inland port environments will be required to draw a valid conclusion.

The authors in [18] used a rig setup to investigate the reaction of a multicopter and its subsystems when exposed to electromagnetic signals. The test rig used in their setup was designed such that it can measure data stream from the flight control board (FCB) as well as the rotor frequencies. Their setup enabled exposure of Device Under Test (DUT) to electric field strength, as high as $70\frac{kV}{m}$.They concluded that the interference threshold of unmanned aerial systems depends on the interference threshold of the FCB.

In [19], the safety and reliability of UAV's data link in a battlefield electromagnetic environment was studied. This was carried out using continuous-wave electromagnetic built in the laboratory serving as the interference source. The conclusion drawn from their results was that UAV's data link is very susceptible to RF noise. They also observed that different polarization of radiated electromagnetic noise has a direct relation with the threshold beyond which the communication between UAV and controller is disrupted.

From the above discussions, it can be seen that the existing works in the literature primarily focus on specific test scenarios and therefore test RF frequencies that are likely to be encountered in their respective cases. Furthermore, all of the above-mentioned works use only a single UAV platform which is either a customized platform or a general-purpose platform. In our work, however, the objective is quite different. In this study, we subject two different general-purpose UAV platforms to the electromagnetic compatibility testing in our quest for the selection of a platform that will perform reliably in the unstructured environment that is likely to be encountered around bridges.

3. Experiment Design

The main equipment items for RF immunity testing are UAV's cockpit, Agilent N9310A RF signal generator, Agilent CXA 9000 signal analyzer, and a UAV. We performed this experiment using two different general-purpose UAVs so as to choose the one that can withstand the RF interference. To avoid commercial advertisement, in the remaining sections of this paper, we will refer to these two drones used in this study as UAV 1 and UAV 2.

The ground station/cockpit of the UAV 1 was equipped with an LCD screen for live video preview during the inspection. In addition, it displayed speed, altitude, GPS status, data link status, and battery status information on the LCD screen. UAV 2 used a third-party First-Person View (FPV) that was installed on a smartphone and attached to the controller to provide a real-time video preview. The FPV also provides information about speed, altitude, GPS status, data link status and battery status. In addition to the above, the cockpit was responsible for issuing commands to remotely pilot the UAV. All the aforementioned information including remote control signals are transmitted via the RF channels, and thus, it can be impacted by RF interference. Table 1, indicates the frequencies the platforms under test transmits on.

Table 1: RF Frequencies used by the Platforms under test.

Platform	RF (GHz)	Data Link (GHz)
UAV 1	2.4	5.8
UAV 2	2.4	5.8

We used the Agilent N9310A signal generator to generate electromagnetic interference in the test area. It supports frequencies in the range of 9kHz – 3GHz, and thus, its range covers the operating frequency for the UAV's communication channels as well as other RF signals that are likely to interfere with the UAV's channels. Furthermore, we used the Agilent CXA 9000 signal analyzer to measure the environmental average RF signal power levels, the UAV's Remote Command (RC) transmission power, and the interference generated by Agilent N9310A signal generator. It supported frequencies over the ranges of 700MHz - 3 GHz. The signal generator and analyzer were connected to a wide-band antenna that supports their respective frequencies. Figure 1 shows the setup used for conducting the tests.

Since this experiment involved RF interference generation,

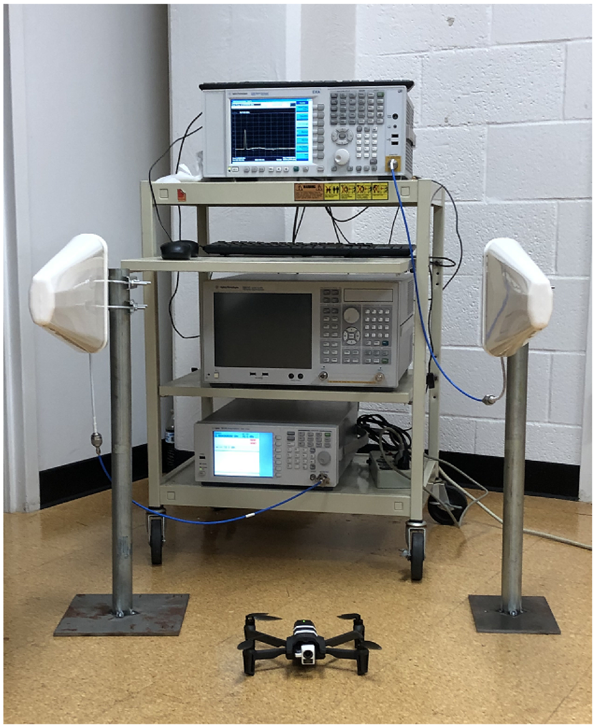

Figure 1: The experiment setup.

we ensured it was carried out in accordance with the Federal Aviation Authority (FAA) and the Federal Communication Commission (FCC) regulations. The tests were conducted away from commercial radio, TV antennas, and FAA or military radars to ensure that our tests do not impact their services.

Test Procedure

As an initial step, we scanned the frequency range of 2GHz-3GHz to establish the environment's RF signal power using RF Signal Analyzer. We then turned on the UAV and controller/cockpit. Figure 2 shows the test set up. The UAV was then positioned initially at a distance of less than 1m from the signal generator. At this point, no interference was observed. We checked the status of the RF and video feed in addition to all other information discussed above to ensure that the UAV is operating as expected.

We then introduced the RF noise using the RF signal generator. The noise was introduced using two methods. In the first method, a 15dBm random RF signal was generated in the Continuous Wave (CW) mode between 2.38 - 2.49GHz bandwidth. In the second method, the RF noise power was increased to its maximum level. It was then swept through the RF frequency band of the UAV's transmitting frequency. The sweeping was done in steps of 1 kHz. In both cases, the UAVs were initially placed close to the interference source and then we kept moving the controller away from it in steps while checking the basic functionalities of the UAV. We also considered a second scenario in which we moved both the controller and UAV away from the RF noise source in steps of about 10m while checking RF and video preview status at each step. The main information that was used to judge the impacts of the interference are RF commands, GPS status, and video camera feed. The above procedure was repeated for the other platform. Figure 1 shows the experiment setup and Figure 2 symbolically shows the experiment procedure for RF interference immunity testing.

4. Experiment Results

Figure 3 depicts the UAV 1's control band together with the environmental noise. We observed a 5dB power level increase above the environmental noise in the bandwidth of 2.395- 2.481GHz, at the time when communication between the UAV and controller was established. The noise in this plot is just the natural environmental noise observed prior to the introduction of artificially generated noise. Similar results were obtained for UAV 2 since they both operated in the same frequency range.

As mentioned in the experimental design Section, the UAVs under test were exposed to RF interference using two methods. The first method involved the generation of a random 15dBm continuous wave RF signal within the UAV's operating frequency range. The second method involved a 20dBm sweeping frequency within the UAV's operating frequency range. The RF noise together with environmental noises and UAV 1 control signal are shown in Figures 4 and 5.

After the introduction of the RF noise using the two methods described above, we checked the RF commands, GPS, and video link status for UAV 1. It was observed that none of the functionalities of UAV 1 were impacted for both the random 15dBm RF noise and 20dBm sweeping noise. Our observations are summarised in table 2.

Table 2: Observed effects of RF noise on UAV 1

RF noise power	Distance of controller from UAV	RC	Video	GPS
15dBm transmitting power	$> 1m$	None	None	None
15dBm transmitting power	$\approx 5m$	None	None	None
15dBm transmitting power	$\approx 10m$	None	None	None
15dBm transmitting power	$\approx 20m$	None	None	None
20dBm transmitting power(sweep)	$\approx 20m$	None	None	None

Using the same setup, we subjected UAV 2 to similar interference levels. We observed that the connection between UAV 2 and its controller is disrupted if the RF signal noise power density is more than $0.00005mW/cm^2$. Although UAV 2 has an inbuilt mechanism to switch to a different frequency band when a current one is impacted by a RF noise, it usually takes about 15sec to make the switch. From Figure 6, it can be observed that when an interference was introduced to the UAV 2's default frequency (2.444GHz), all communications were lost for about 15 seconds. After that, the UAV automatically switched to a different frequency, i.e. 2.461GHz. Furthermore, we observed that most of the functionality of the UAV 2 was impacted even at lower noise power levels used for the UAV 1. The RF noise power above -23 dBm severely impacted the operation of UAV 2. In most cases, GPS, video, and RC signals are impacted (see Figure 7). Also when UAV2 was subjected to a sweeping RF noise

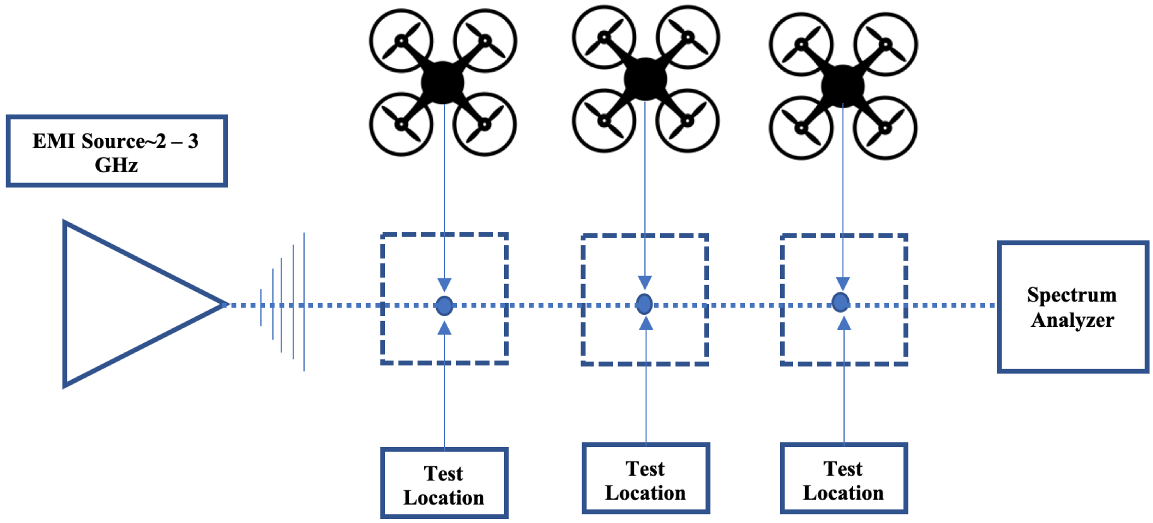

Figure 2: The designed RF interference immunity test setup.

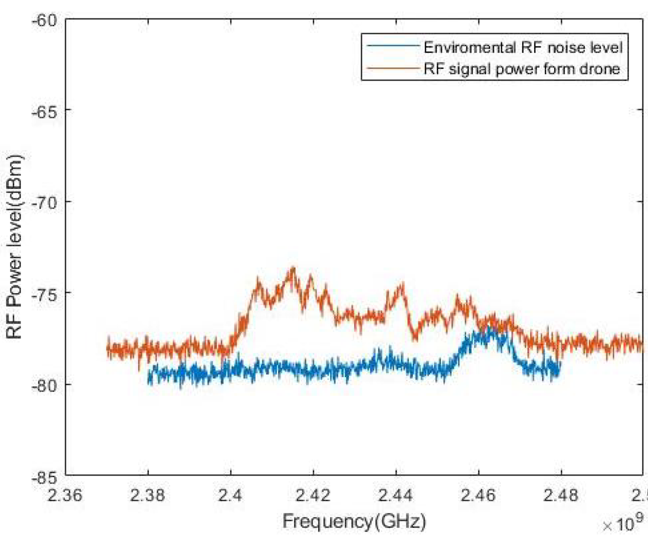

Figure 3: UAV 1 control band and environmental noise.

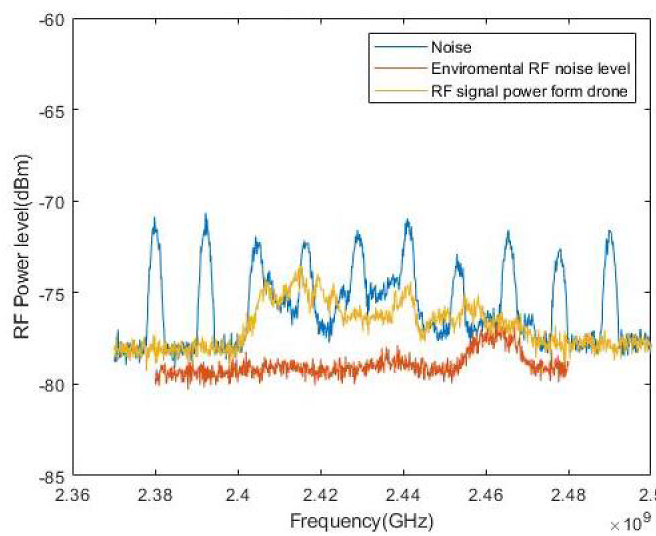

Figure 4: Exposure of UAV 1 to 5 dBm sweeping RF noise.

of 10dBm in the band of its operation, we observed a reduced quality of the video feed even though the RF was working properly. This is shown in Figures 8 and 9.

Table 3: Observed effects of RF noise on UAV 2

RF noise power	Distance of controller from UAV	RC	Video	GPS
-50 dBm transmitting power	$> 1m$	None	None	None
-30 dBm transmitting power	$\approx 1m$	None	None	None
-17 dBm transmitting power	$\approx 1m$	Not OK	Not OK	Not OK
10dBm transmitting power(sweep)	$\approx 6m$	None	Not OK	None

5. Discussions

The experimental results highlighted the importance of RF interference immunity of UAVs as part of the criteria for evaluating their suitability for the bridge inspection application. It was observed that both UAVs used in these experiments adhered to the FCC requirements on RF interference immunity. However, their behavior was very different when RF noises close to their operating frequency were introduced. The UAV 1 handled RF noises, as high as 20 dBm with no observed impacts on RF, GPS, and video feed signals. This can be explained by the fact that the UAV 1 relies on redundant RF channels which can be used to switch to in a very short switching time when a default channel is disrupted. The switching time was so small that no disruptions was recorded

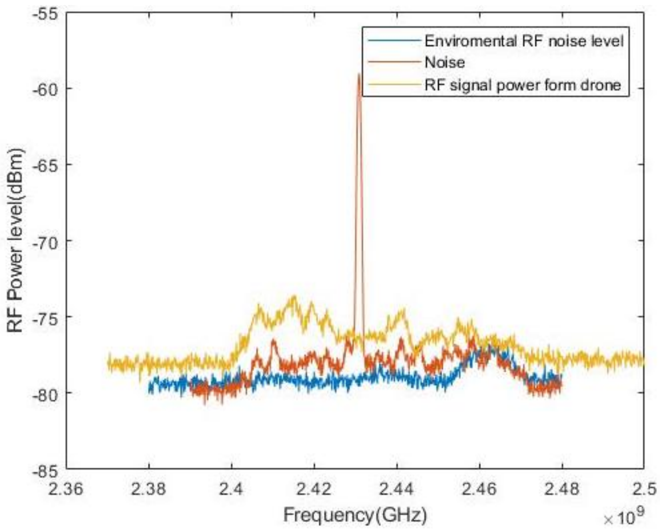

Figure 5: Exposure of UAV 1 to 20 dBm sweeping RF noise.

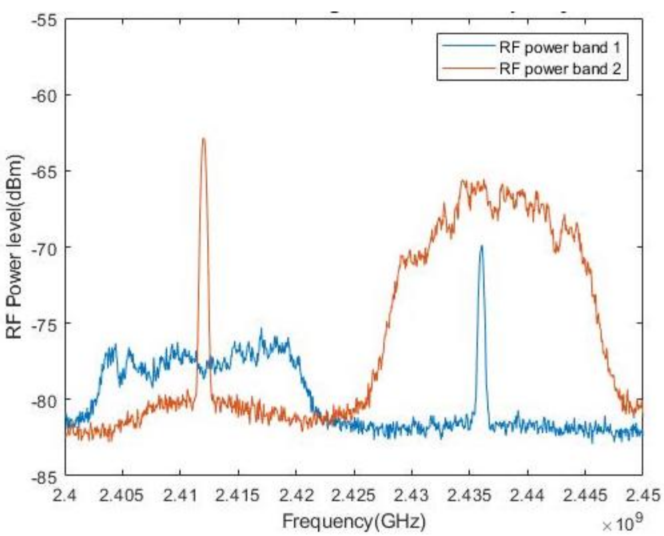

Figure 6: UAV 2 Control bands.

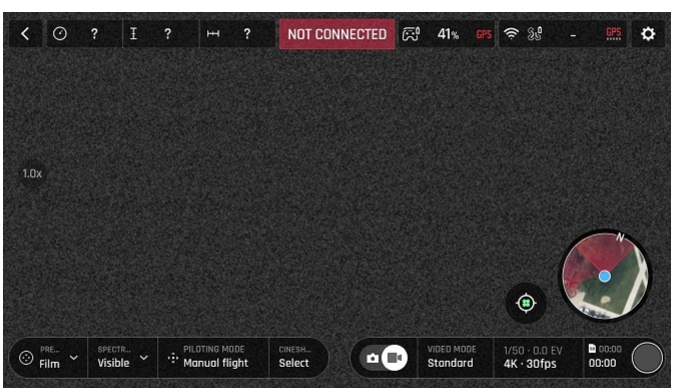

Figure 7: Loss of RC, GPS, and video after RF noise $> -17dBm$ was introduced to UAV2.

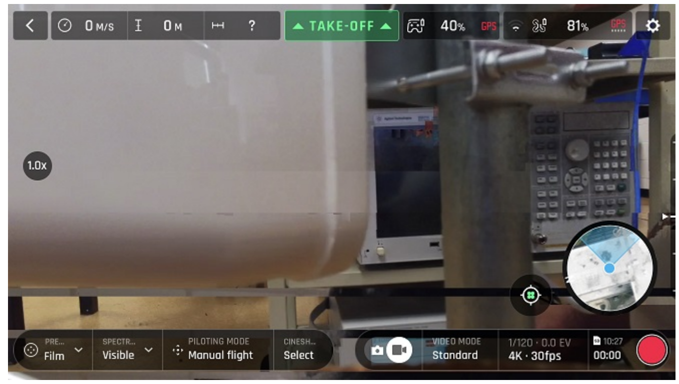

Figure 8: Image quality of UAV 2 before being exposed to RF noise $> -17dBm$.

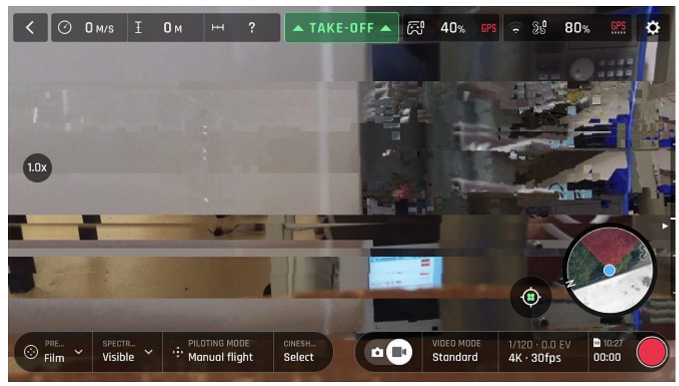

Figure 9: Image quality of UAV 2 after being exposed to RF noise $> -17dBm$.

in its video feed and RF connections. Although UAV 2 used a similar redundancy mechanism for RF and video, the switching times were longer. It took about 15sec to change to the alternate frequency when its default frequency was impacted by RF interference. A delay of 15sec has a high potential of crashing the UAV, especially when navigating in confined spaces around bridges. Furthermore, our results indicated that the UAVs' responses to RF noise depend on the power level of the generated RF noise. We were able to subject UAV 1 to RF noises, as high as 20dBm, without observing any noticeable degradation in its functionality. This was not the case for UAV 2. Even exposure to RF noise of -17 dBm resulted in the loss of GPS, video feed, and RF connection in UAV 2.

The results emphasize the need for evaluation of the RF interference immunity of UAVs intended to be deployed for bridge inspection practices. It is also important to assess the bridge environment for the presence of any potential source of RF noise that can impact the performance of UAVs. This is needed for both the safety of the UAVs and inspection personnel.

6. Conclusion

This experimental study explored the performance of UAVs when operating in environments with RF noise levels which are close to their operating frequencies. The results showed that there is a potential loss of RF communication and video feed in the presence of RF noise interference. This becomes more critical for inspections in confined spaces or when the

UAV is flying beyond line of sight and its only means of situational awareness is through the video feed. In addition, it was shown for one of the UAVs under test, the GPS can also get impacted when electromagnetic interference is present. Furthermore, the results revealed that some UAVs can have better RF immunity than others depending on the switching time of their redundancy mechanism if they are equipped with. For example, one of the UAVs under test in this study was able to withstand RF noise as high as 20 dBm with no observable impacts on its functionality while the other UAV was not able to withstand noise greater -23 dBm. Therefore, it is important to take this factor into account as one of the UAV selection criteria for the bridge inspection application whose surrounding environments are unstructured with a very high likelihood of the presence of RF noise.

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References

[1] T. Zhao, D. Doll, D. Wang, and Y. Chen, "A new framework for uav-based remote sensing data processing and its application in almond water stress quantification," in *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2017, pp. 1794–1799.

[2] S. Waharte and N. Trigoni, "Supporting search and rescue operations with uavs," in *2010 International Conference on Emerging Security Technologies*, 2010, pp. 142–147.

[3] A. Girma, N. Bahadori, M. Sarkar, T. G. Tadewos, M. R. Behnia, M. N. Mahmoud, A. Karimoddini, and A. Homaifar, "Iot-enabled autonomous system collaboration for disaster-area management," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 5, pp. 1249–1262, 2020.

[4] M. A. Balaban, T. W. Mastaglio, and C. J. Lynch, "Analysis of future uas-based delivery," in *2016 Winter Simulation Conference (WSC)*, 2016, pp. 1595–1606.

[5] Z. Zaheer, A. Usmani, E. Khan, and M. A. Qadeer, "Aerial surveillance system using uav," in *2016 Thirteenth International Conference on Wireless and Optical Communications Networks (WOCN)*, 2016, pp. 1–7.

[6] N. Namvar, A. Homaifar, A. Karimoddini, and B. Maham, "Heterogeneous uav cells: An effective resource allocation scheme for maximum coverage performance," *IEEE Access*, vol. 7, pp. 164 708–164 719, 2019.

[7] D. W. Matolak, "Unmanned aerial vehicles: Communications challenges and future aerial networking," in *2015 International Conference on Computing, Networking and Communications (ICNC)*, 2015, pp. 567–572.

[8] K. Vinh, S. Gebreyohannes, and A. Karimoddini, "An area-decomposition based approach for cooperative tasking and coordination of uavs in a search and coverage mission," in *2019 IEEE Aerospace Conference*, 2019, pp. 1–8.

[9] H. Shakhatreh, A. H. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani, "Unmanned aerial vehicles (uavs): A survey on civil applications and key research challenges," *IEEE Access*, vol. 7, pp. 48 572–48 634, 2019.

[10] F. H. Authority, "Use of small unmanned aerial system for bridge inspection," *Tech Brief*, 2019.

[11] G. Shuxia, D. Zhongyao, H. Zhantao, and H. Chufeng, "Simulation of dynamic electromagnetic interference environment for unmanned aerial vehicle data link," *China Communications*, vol. 10, no. 7, pp. 19–28, 2013.

[12] F. Box, L. Globus, Yan-Shek Hoh, R. Snow, and J. Chadwick, "Potential rf interference to control links of small unmanned aircraft," in *2008 Integrated Communications, Navigation and Surveillance Conference*, 2008, pp. 1–12.

[13] 911 Security. Drone communication - data link. [Online]. Available: https://www.911security.com/learn/airspace-security/drone-fundamentals/drone-communication-data-link#:~:text=There%20are%20various%20frequencies%20used,approximately%204%20miles%20of%20range.

[14] J. Natarian, "Effects of radio frequency interference on an 802.11a wireless ad-hoc network," in *Proceedings of the IEEE 2010 National Aerospace Electronics Conference*, 2010, pp. 237–239.

[15] J. Jung, C. Ippolito, C. Rogers, R. Kerczewski, A. Downey, and K. Matheou, "Small unmanned aircraft electromagnetic interference (emi) initial assessment," in *2018 Integrated Communications, Navigation, Surveillance Conference (ICNS)*, 2018, pp. 2A3–1–2A3–10.

[16] L. Torrero, P. Mollo, A. Molino, and A. Perotti, "Rf immunity testing of an unmanned aerial vehicle platform under strong em field conditions," in *2013 7th European Conference on Antennas and Propagation (EuCAP)*, 2013, pp. 263–267.

[17] C. Adami, S. Chmel, M. Jöster, T. Pusch, and M. Suhrke, "Definition and test of the electromagnetic immunity of uas for first responders," *Advances in Radio Science*, vol. 13, pp. 141–147, 11 2015.

[18] F. Burghardt and H. Garbe, "Development of a test rig to measure the em-susceptibility of an unmanned aerial vehicle," 08 2017, pp. 1–4.

[19] Zhang Tao, Chen Yazhou, and Cheng Erwei, "Continuous wave radiation effects on uav data link system," in *2013 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference*, 2013, pp. 321–324.

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