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Assessing the Vulnerability of Unmanned Aircraft Systems to Directed Acoustic Energy

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ABSTRACT

The increasingly large payloads of **U**nmanned **A**ircraft **S**ystems (UASs) are *exponentially* increasing the threat to the nuclear enterprise. Current mitigation using RF interference is effective, but not feasible for fully autonomous systems and is prohibited in many areas. A new approach to UAS threat mitigation is needed that does not create radio interference but is effective against any type of vehicle. At the present time there is no commercial counter-UAS system that directly assaults the mems gyros and accelerometers in the **I**nertial **M**easurement **U**nit on the aircraft. But lab testing has revealed resonances in some IMUs that make them susceptible to moderate amplitude acoustic monotones. Sandia's energetic materials facility has enabled a quick and thorough exploration of UAS vulnerability to directed acoustic energy by using intense acoustic impulses to destabilize or down a UAS. We have: 1) detonated/deflagrated explosive charges of various sizes; 2) accurately measured impulse pressure and pulse duration; 3) determined what magnitude of acoustic insult to the IMU disrupts flight and for how long and; 4) determined if the air blast/shock wave on aircraft/propellers disrupts flight.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

We have conducted extensive tests of the effect of pressure impulses on UAS flight stability created by detonating various amounts of C-4 (an *ideal* explosive) on the flight of a UAS whose IMU is enclosed in a durable plastic housing. Parameters investigated were the amount of charge, the distance of the UAV from the charge, and the direction of the charge from the UAS (horizontal or vertical). High-speed video and overpressure data were recorded, data was downloaded from the UAS *Inertial Measurement Unit*, and illustrative shadowgraphs were made. In many cases we were able to ground the UAS, apparently due to nullifying the output of the IMU. The UAS was not permanently damaged! The pressure impulse is proportional to the momentum transfer to the UAS, but it was found that destabilization was not a function of the impulse, but seemed more to be dependent on the peak overpressure. Based on these results we can approach funding to develop a directed energy system with the same level of overpressure for further testing. Such a system would use only a very small fraction of the charges we used for these tests.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
UAS	Unmanned Aerial System (includes flight controller)
UAV	Unmanned Aerial Vehicle
IMU	Inertial Measurement Unit

1. INTRODUCTION AND BACKGROUND

A variety of approaches have been developed for mitigating malicious attacks from UAVs, but none of these are capable of nondestructively capturing autonomous UAVs with high reliability, and without incurring significant regulatory or safety issues. For these reasons a new approach is needed. In this report we describe tests that examine the effect of various blast overpressure pulses on the stability of UAVs and ascertain the overpressure required to down a UAV. But before we describe these tests it is worthwhile providing a little context, including previous acoustic work and the kind of acoustic systems that already exist.

Current approaches. Nondestructive approaches under current development include signal interference and entanglement with nets. Signal interference is an effective way to disrupt communications to the UAV, but can cause unwanted interference with other systems, including aircraft. For this reason, the emission of interfering signals is highly regulated and would not be effective on autonomous UAVs in any case. Interfering with positioning signals (GPS, GNSS) can be effective on autonomous UAVs, but could also violate regulations, since this interference would affect all devices in the vicinity dependent on such signals. Using UAVs to capture malevolent UAVs with nets is also under development, but field tests have not yet shown a high probability of success and this approach has a long response time. Even if this approach is developed further, a faster UAV would be an effective countermeasure. Destructive techniques that involve projectiles and explosives have obvious safety concerns near critical facilities and congested urban environments. EMPs can disable some of the electronics on UAVs but threaten electronic systems in the vicinity. Lasers have been explored but are expensive systems that are strongly affected by weather conditions that scatter light, such as fog, rain, snow, hail and blowing dust.

Acoustic approaches. Acoustic systems are attractive for a number of reasons. They have enjoyed a century of development, can be *extremely* powerful, require little to no maintenance, and can be rapidly directed and focused on any target through the use of phased arrays. Finally, the speed of sound greatly exceeds the speed of UAVs so target leading will be manageable at reasonable ranges. There are two approaches of interest: narrow band sound carefully tailored to attack a particular IMU and intense broadband sound, possibly pulsed.

Tailored sound: It is not surprising that the MEMS gyros and accelerometers in the inertial measurement unit (IMU) of a drone are susceptible to an acoustic attack, either by powerful broadband pulsed or CW acoustic energy, or by narrowband CW tailored to frequencies to which the components in the IMU are found to be vulnerable, due to resonances of the MEMS devices. In fact, published research on the influence of sound on MEMs gyros dates back at least to 2007 [1].

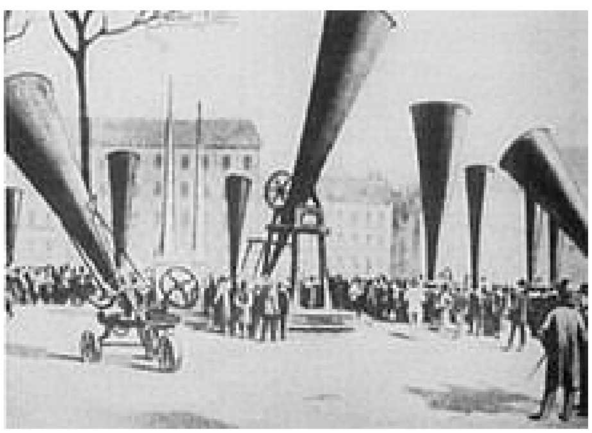
In an extensive study by a Korean group [2], fifteen different MEMs gyros were exposed to sound generated by a speaker in close proximity to the IMU and the output from the three axes of the gyro was collected in order to determine if any resonances occurred and at what frequencies. The frequency range investigated was from 100Hz to 30kHz. In eight of the fifteen gyros no resonances were found in this range, in six gyros resonances occurred in the ultrasound band from 20 to 30kHz and in one gyro a resonance was found at ~8kHz. In four cases the resonance affected the output of all three axes, in three cases it affected only one axis. It was possible to use sound tuned to the resonance to crash a UAV whose IMU utilized a gyro whose output was affected on all three axes, but a UAV using a gyro whose output was affected along only one axis was unaffected.

A group at the University of Michigan [3] carried out some clever studies of manipulating capacitance-based MEMs comb accelerometers. They used sound in the range of 2-30kHz to identify resonances in twenty different models of accelerometers, and found resonances throughout the audible range, mostly around 3-6kHz, in all but three models. These resonances were generally fairly broad. They looked at the output signal from the amplifier, to which the signal from the accelerometer is routed via a low-pass filter, intended to prevent aliasing by the analog to digital converter. By subjecting the IMU to sound at the resonant frequency they could produce two effects: 1) creating a periodic output signal of zero mean at the resonant frequency and; 2) creating a periodic signal with a dc offset due to asymmetric amplifier clipping. By amplitude modulating their nuisance signal they could actually take control of an RC car controlled by a cell phone with an embedded accelerometer, simply by playing music with embedded resonant acoustical signals on the cell phone. They then described software that could mitigate the biasing, but were unable to eliminate the periodic output. They did not conduct experiments on UAVs.

An anti-UAV system taking this approach would likely be based on phased arrays (at right). Phased arrays are commonly used for beam forming in radar systems and can also be used to both focus and direct sound, as shown in the example at right. Phased arrays would enable very rapid beam orientation and focusing, which is essential for tracking fast-moving UAVs. The MEMS accelerometers have resonances in the audible range, but for the MEMs gyros these resonances are in the ultrasound. Phased arrays of piezo emitters operating at very high frequencies are used in medical ultrasound imaging devices, as well as in industrial applications, such as weld inspection. (The general term for this imaging technique is Phased Array Ultrasonics.) Because of the short wavelength, ultrasound can be easily focused into a narrow beam. However, the viscosity of air strongly attenuates high-frequency ultrasound, and this attenuation increases quadratically with frequency, so the range of such a system would diminish rapidly as the ultrasound frequency increases. The resonances identified thus far are only slightly above 20kHz, so the range of such sound would be acceptable.

Broadband sound: Not all MEMs sensors tested demonstrated resonances, and those that did required those resonances to be identified in order to manipulate signals coming from the IMU. Although coupling sound to resonances of the MEMs device is elegant in its efficiency, a brute force approach of intense sound, pulsed or broadband CW, might also be effective, and has the advantage that the resonances of the MEMs devices do not need to be known. Pulsed sound is particularly attractive because it can be very intense (see examples below) and the Fourier spectrum of an impulse is a broad sound spectrum, with the usual uncertainty principle governing the product of the pulse time and the bandwidth of the emission. Unfortunately, little work has been in this area. We'll now describe some of the currently available devices capable of directing intense sound.

Directed acoustic energy devices: Directed acoustic energy is a surprisingly old concept, arguably dating to the development of animal screams and roars intended to petrify enemies or prey, and certainly to the development of focused pulsed sound, such as the sonar produced by the fluid acoustical lenses in the head of the sperm whale to hunt giant squid in the lightless depths of the seas. But in the human context hail cannons are an early example of using intense, directed sound to achieve effects beyond the merely psychological or to prey location. Hail cannons are a brute force device that fire an intense blast towards the heavens to discourage the development of hail by fragmenting nascent hail, or so it is thought. These cannons were popular around the turn of the nineteenth century in Europe, where they were positioned around crop land as a wall of defense against hail damage. The idea was so popular that in Italy in 1900 there were already 1,630 hail cannons. Doubts about the efficacy of hail cannons led to their demise, but there has been a recent resurgence of interest in these, which has resulted in the development of the more powerful acetylene gas fueled systems currently manufactured in America, with even more powerful "vortex cannons" under current development. In recent years both Nissan in America and Volkswagon in Mexico have used vortex cannons to try to prevent hail damage to the new cars outside their production facilities. Noise complaints ended these experiments.



The repetition rate of the current generation of vortex cannons is about 1Hz, which would possibly allow the potentially destabilized UAV to recover from a blast before the next blast occurs. However, there is nothing that fundamentally prevents the repetition rate from increasing to the point where the UAV is constantly "on the ropes" and is continuously destabilized, precipitating a crash. In fact, during WWII Germany developed this basic concept into a weapon that operated at 44Hz.

> "In the early 1940s Nazi engineers had managed to develop a sonic cannon that could literally shake a person apart from the inside. Or at least that's what they claimed. Designed by Dr. Richard Wallauschek, the cannon consisted of a methane gas combustion chamber leading to two large parabolic reflectors, the final version of which had a diameter over 3m. The "dishes" were pulse detonated at around 44Hz and were connected to a chamber composed of several sub-units firing tubes. These tubes would allow a mixture of methane and oxygen in the combustion chamber, which when ignited, would turn these gases into noise that could kill. This infrasound, magnified by the dish reflectors, caused vertigo and nausea at 300 yards by vibrating the middle ear bones and shaking the cochlear fluid within the inner ear. Apparently, the sound waves created pressures that could kill a man 50 meters away in half a minute. To say the least, this is very unconvincing, since this supposed Sonic cannon was only tested on laboratory animals and was never tested on human beings."

Shaking bones in the inner ear is much akin to rattling accelerometers and gyros in the IMU of a UAV, so vortex cannons are one approach worth investigating. There is an American company that could be engaged for testing.

The Long Range Acoustic Device (LRAD), a sonic cannon currently used for crowd dispersal, can produce highly directed, extremely intense sound levels (~150 to 162dB at 1m, depending on the model) over a frequency range of 2.5-3kHz. The stated range is up to 8,900m for the most powerful model, though it is not clear how this range is defined. This device is currently used for long-range messaging and crowd control and can be focused to a relatively small solid angle. When used for crowd control it emits extremely irritating sounds. If UAVs were found to be susceptible to particular frequencies, and LRAD could be designed to emit those bands.

Identifying vulnerabilities. The experimental work done so far on identifying resonant frequencies has used the modest sound levels produced by consumer-level audio equipment (110dB) to alter the output of the MEMs sensors. Intense sounds could be investigated by adhering piezos directly to the IMU along its three orthogonal axes. The analog or digital output of the MEMS ICs could then be monitored to determine the effect of the piezos as a function of their frequency and amplitude. Sound of a single frequency or pulses could be sent to the piezos to create a broadband disturbance or noise could be generated. Could appropriate signals to an IMU embedded in a hovering UAV control or crash a UAV?

What sound pressure level is required to create the desired disturbance? It might be that this level of sound can be developed with commercially available audio equipment, especially if placed in a resonant chamber. If not, then other facilities exist that can create very loud sounds, and we can arrange to use these. The most powerful facility is NASAs Reverberant Acoustic Test Facility at left, which can produce CW sound levels as low as 120 dB and as high as 163dB within the twenty seven selectable 1/3 octave bands from 31.5 to 1,250Hz. Their facility can be rented and the costs are not prohibitive. It would be interesting to fly a UAV and determine the sound pressure level required to destabilize at each of the available frequency bands. Note: To achieve the high sound pressure levels they are capable of, the NASA horns are driven by nitrogen gas, obtained by boiling liquid nitrogen, up to 2,400 gallons per minute. Lower sound levels, but up to 120dB can produced at another facility by more conventional electrical systems, at a much lower cost.

Intense pulsed sound experiments could be done in conjunction with Newton Systems, the company that has recently developed an extremely powerful vortex cannon. This cannon can blow a mans hat off at 1000m, or so they claim. Hopefully the vortex cannon will cause the IMU to destabilize the UAV, at least for some measurable time. This timescale can be determined and the required pulse rate computed to keep the UAV destabilized so that it crashes or can be recovered. Another important issue is at what range, if any, the vortex cannon can destabilize the UAV. If the range and pulse rate are acceptable, then follow-on work could pursue the design and development of this approach to an anti-UAV system.

Finally, really intense pulsed sound can be produced at Sandia’s explosives testing facilities, and this is the approach we have taken. It is good that we chose this route, as higher-than-expected overpressures were required to knock down the UAV. Enough of this background materials, now we will describe our tests and the results they produced.

2. EFFECT OF ACOUSTIC IMPULSES ON STABILITY OF A UAV

In the following we describe tests of the effect of pressure impulses on UAV flight stability. The UAV was a DGI Phantom 4 Pro quadracopter whose IMU (Inertial Measurement Unit) was protected by a strong plastic housing. Extensive acoustic testing at Sandia had shown the IMU of this UAV to be unaffected by strong monotones over the bandwidth of 40 to 30,000Hz, so this UAV was considered by us to be a tough target for acoustic impulses. Pressure impulses were created by detonating amounts ranging from 1/8 to 2lb of the ideal explosive C-4 at distances of 4 to 10 ft from the UAV.

The parameters investigated were the amount of charge, the distance of the UAV from the charge, and the direction of the charge from the UAV (horizontal or vertical). We also tested the UAV with and without payloads, since payloads could compromise stability. The time-resolved impulse pressures at the UAV distance were measured by highly accurate piezoelectric transducers and high-speed videos and shadowgraphs were made. In addition, data was downloaded from the gyros and accelerometer of the IMU. In some tests we were able to ground the UAV, apparently due to nullifying the output of the IMU. But in all cases the UAV was not permanently damaged.

The test set-up can be seen in Figure 1. Here a spherical charge of C-4 explosive is shown over the X taped on to the plate laying on the ground. Two piezoelectric pressure transducers can be seen that are directed at the charge (they look like spears). To the upper left of this image can be seen the back enclosure of the test site, which consists of steel sidewalls, a backwall, and a ceiling. This enclosure creatse shockwave reflections, but is a necessary safety precaution. The UAV is then flown remotely, from the control room, while the charge is remotely detonated from that room. The DGI Phantom 4 Pro can be seen on top of the inverted grey garbage can. Not seen in this photo is the netting that was subsequently put up to contain the UAV.

Figure 2-1. The explosive charge and the two piezoelectric transducers at the test range.

Thirteen tests were completed at this facility, as shown in the table below, some of these downed the UAV (Fail) and some did not (No Fail), so we were successful in determining the required conditions for downing. The lowest peak overpressure generated with the ideal explosive C-4 was 3 psi and the highest was 40.6 psi. One experiment was done with the non-ideal explosive Pyrodex, because we were interested in seeing the effect a relatively long pressure pulse would have on the UAV. The peak pressure in this case was a mere 0.86 psi. The peak overpressure impulse was computed by time integrating the overpressure from the initial shockwave. We did not include contributions from the subsequent reflected shockwaves, which come from both the ground and the steel back enclosure of the test site. The overpressure impulse is proportional to the momentum transfer to the UAV. The peak impulse ranged from 1.8 to 15.2 psi-ms for the C-4 and was 1.3 psi-ms for the Pyrodex. A measure of the time of the overpressure impulse can be computed by dividing the peak impulse by the peak pressure. At 4 feet this gives a time of ~0.25 ms, whereas at 9 feet this time increases to 0.70 ms. The pulse width increases essentially linearly with distance. By controlling the charge distance we can therefore independently control the peak pressure and the pulse duration, which turned out to be an important aspect of these experiments.

Table I. Tests performed and the results.

Shot #	UAS Test #	Charge NEW	Distance to UAS (ft)	Peak Pressure (psig)	Peak Impulse (psi-ms)	Fail/No-Fail
1						
2						
3	1	0.5	9	6.6	4.6	No Fail
4	2	0.125	9	3	1.8	No Fail
5	3	1	9	9.9	7.1	No Fail
6	4	0.125	4	11.6	3.8	No Fail
7	5	0.5	4	34	8.25	Fail
8	6	0.5	4	37	8.8	Fail
9	7	0.5	9	6.5	5.25	No Fail
10	8	1	9	9.3	6.4	No Fail
11	9	30 grams Pyrodex/25 grams AL		0.86	1.3	No fail
12	10	0.375	4	27.6	6.9	Fail
13	11	2	6	40.6	15.2	Fail
14	12	0.68	10	5.9	4.6	No Fail
15	13	0.375	4	24.9	7.6	Fail

Before giving the results of these experiments it is useful to show key frames of a couple of the shadowgraphs we collected. Shadowgraphs were captured with high speed cameras so the interaction of the shockwave with the UAV could be visualized. The first example shadowgraph is given in Figure 2, wherein a 3/8 lb of C-4 was detonated just 4 feet *under* the UAV. This resulted in a peak overpressure of 24.9 psi and a peak pressure impulse of 7.6 psi-ms. Time advances from left to right. In the second frame the shockwave is just contact the UAV, in the fourth frame it is clear that this shockwave has bent the propellers upward. In this frame the reflected ground wave can be seen just contacting the UAV. The final frame shows the severely upset UAV on its way to crashing, engulfed by the smoke from the explosive.

Shot 15 (0.375 lb C4 NEW – 4' away - vertical blast orientation)

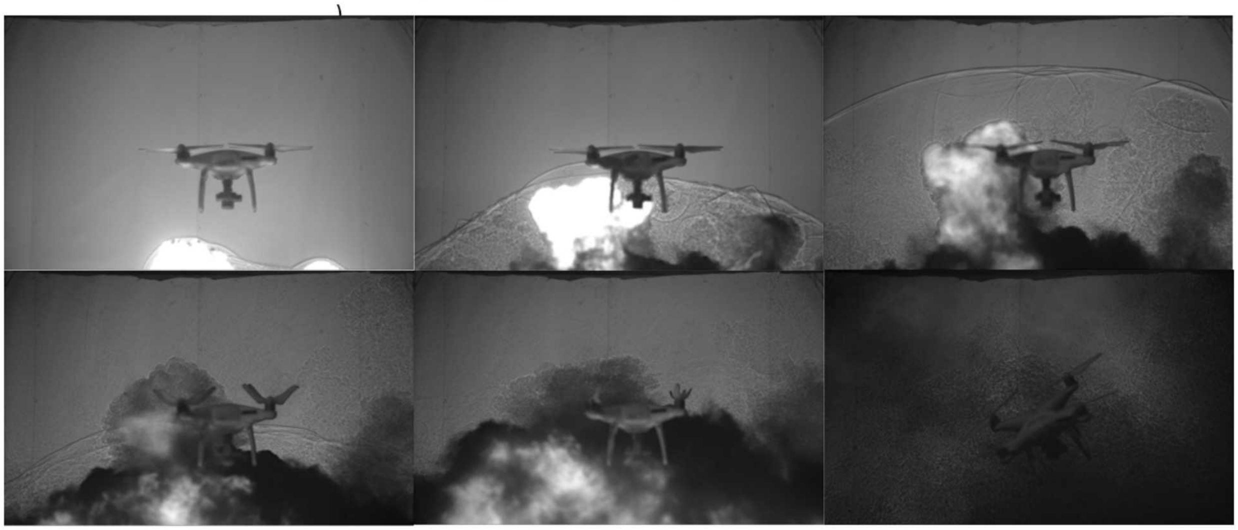


Figure 2-2. Shock wave hits the UAV from below, bending the propellers and destabilizing the UAV.

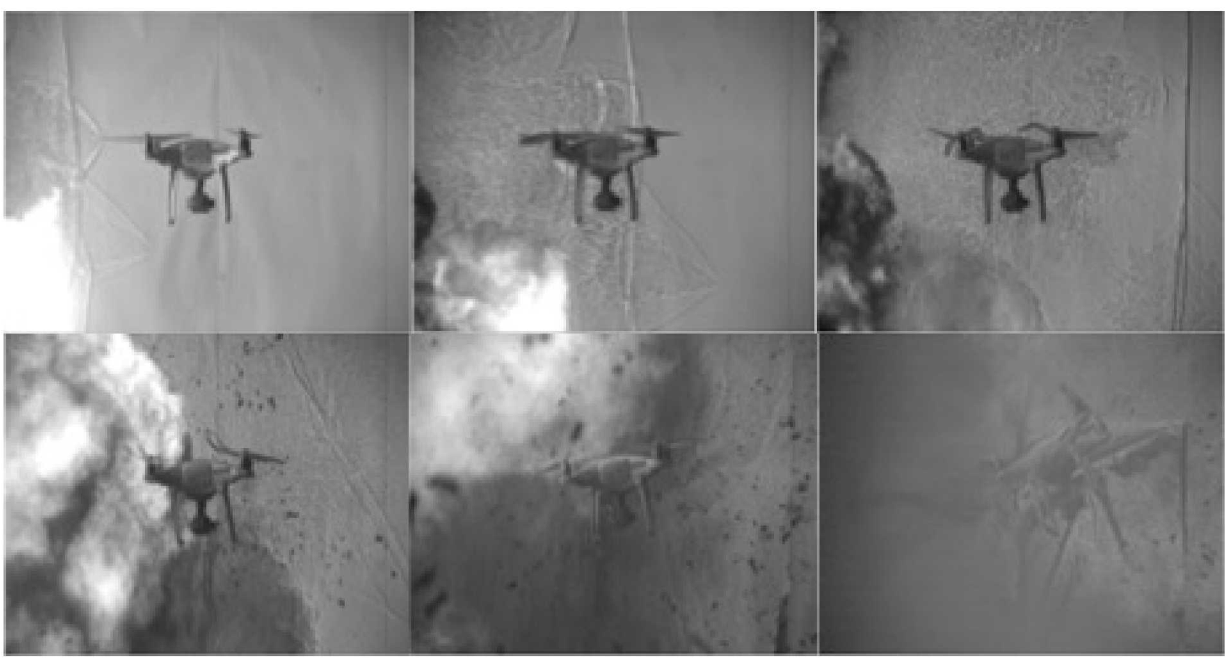


Figure 2-3. Shock wave hits the UAV from the left side, bending the propellers and destabilizing the UAV.

The shadowgraphs in Figure 3 were collected for a 2 lb charge of C-4 in the horizontal plane of the UAV and just 6 ft away. This resulted in a peak overpressure of 40.6 psi and a peak pressure impulse of 15.2 psi-ms. Once again the propellers bend and the UAV is destabilized and crashed, though without permanent damage. The debris seen in the final three frames is from the cardboard tube used to hold the explosive charge. This debris was not the cause of the crashing.

We witnessed two types of UAV response to these shockwaves. In the no-fail cases the UAV at most merely dropped a few feet and restabilized. In the fail cases the UAV generally crashed onto its back, but in one particularly humorous case the UAV actually sped off in a westerly direction and crashed into the netting used to contain it. Its IMU was seriously confused to say the least, though the attempt to escape seemed reasonable.

Examining the IMU data shows that in the cases where the UAV crashed, the output from the MEMS gyros and accelerometers flatlined after the impulse. Such data are shown in Figure 4, where the x, y, z components of the accelerometer are shown before and after the impulse. In contrast are the data shown in Figure 5 for a test that did not crash the UAV.

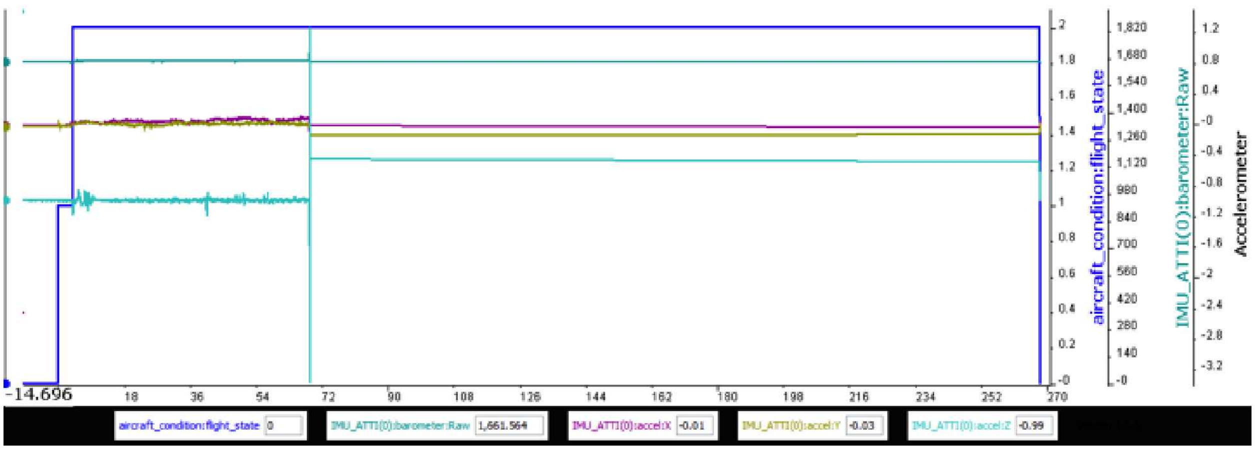


Figure 2-4. Example of flatlined accelerometer output that occurred as a result of an acoustic impulse that crashed the UAV. The gyro output also flatlined. The abscissa is time. The charge was detonated at about 68 seconds.

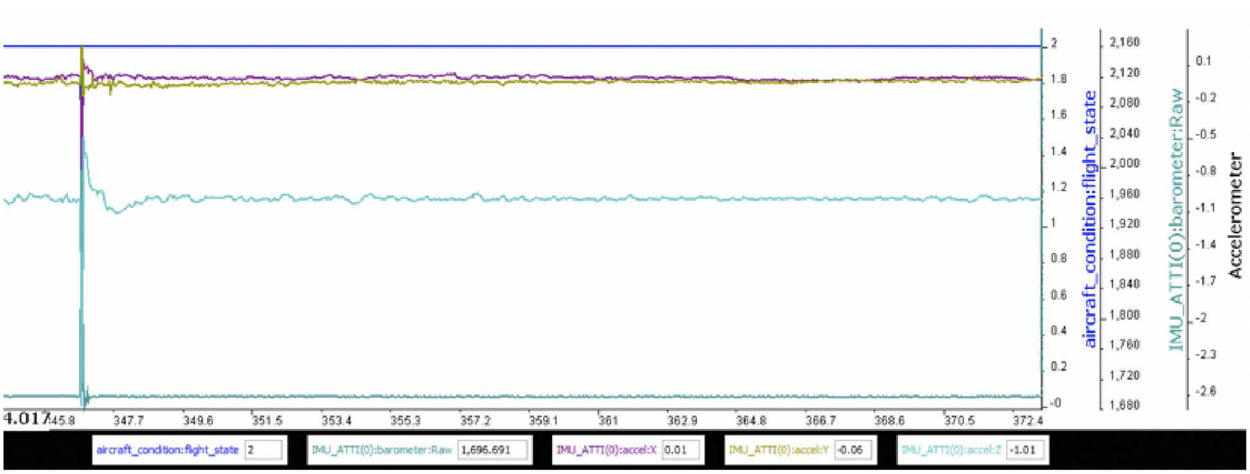


Figure 2-5. Example of the accelerometer output that occurred as a result of an acoustic impulse that did not crash the UAV. The charge was detonated at about 346 seconds, causing a disruption in the steady output, but the UAV restabilized after just a few seconds.

This accelerometer output has an abrupt upswing immediately following the blast, especially along the z axis. It then falls below its stable value as the UAV stops dropping. The output returns to normal after a couple of seconds, when the UAV stabilizes some 3 feet below its initial position.

The whole concept of this LDRD is to determine the conditions required to crash a UAV. The DGI Phantom 4 Pro quadracopter we chose ended up being much more robust than expected, in fact we were amazed at the abuse it could take. We never inflicted any permanent damage, though we did have to reboot the system in many cases in order for it to fly again. And a few propellers were chipped by debris, but that was the extent of the damage.

The test results are summarized on a plot whose ordinate is the peak overpressure impulse and whose abscissa is the peak overpressure of the impulse. Each test we ran is indicated by a single point, colored in blue if the UAV didn't crash and gold if the UAV did crash. One might expect that it would be the impulse that would crash the UAV, since the impulse is proportional to the momentum transfer to the UAV, but this assumption would only be valid on timescales short compared to the time it would take a UAV to respond to the pressure impulse. The limited test data we collected shows that it is the peak overpressure that correlates with crashing. Peak overpressures greater than 27 psi always resulted in crashes, regardless of the impulse, at least over that range of impulses we are able to generate. It would be useful to collect more data in the interval between 12 and 27 psi, and to create much larger impulses at low peak pressures. The latter would have required a much larger staging area, which was beyond the scope of this program. In any case, quite a few more tests would be required to fill out the fail/no fail "phase boundary." These test results provide valuable information that can be used to design a directed energy system with the same level of overpressure for further testing.

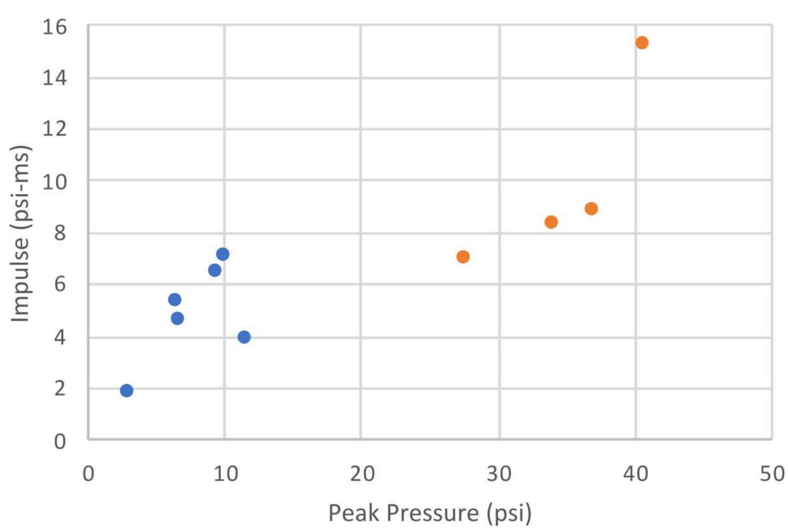


Figure 2-6. A "phase diagram" of the effect of blast shockwaves on the stability of UAVs.

Conclusions. We have found that shock waves of sufficient overpressure can crash the DGI Phantom 4 Pro. But we used large charges and close distances for these spherical blast tests, which would seem to suggest that the shockwave approach is impractical. However, a directed energy system would use only a very small fraction of the amount we used for these tests. For example, a UAV having a cross section of 1 sq. ft. (probably an overestimate) is exposed to only ~0.3% of the blast area from a charge 5 feet away. So if it takes 0.5 lbs of C-4 in a spherical blast to crash the UAV at this distance, it would only take 11 grains (7000 grains per lb) if the blast could be perfectly directed. This is probably an underestimate, but it wouldn't take much C-4 in any case. The most logical next step in testing would therefore be to start testing with a directed energy system, such as a cannon barrel or a parabolic reflector. The cannon barrel would be the inexpensive route. A second direction for this testing is to fill out the phase boundary in Figure 6 by testing in a much larger area.

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