Engineering Education Using Inexpensive Drones

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Introduction and context

Raging wildfires, destructive tornadoes, ravaging floods, and devastating hurricanes are a few of the natural disasters that plague our world. To better understand the conditions that lead to these disasters, scientists need a wide-array of tools and techniques. Engineering creative solutions to some of the world's most complex problems is critical to answer questions and improve forecasts that can protect life and property.

The National Center for Atmospheric Research (NCAR) is a leader in world-class research in Earth System Science. Sponsored by the National Science Foundation (NSF) and managed by the University Corporation for Atmospheric Research (UCAR), NCAR focuses on important atmospheric research problems that require major commitments of resources and a wide range of science talent over extended periods of time. To accomplish this, NCAR employs various technologies on many types of platforms to observe, study, and better understand the atmosphere and how it relates to other spheres (e.g., biosphere, hydrosphere) in the Earth's system. NSF/NCAR aircraft equipped with instrumentation help scientists better understand Earth's atmosphere in a variety of sometimes challenging environmental conditions. Additionally, instruments attached to expendable balloons or dropsondes provide data about dangerous phenomena that are not conducive to study via human-flown aircraft.

Staff at the UCAR Center for Science Education (SciEd) develop learning experiences to help students and the public better understand our changing world through active learning resources. Engineering Experiences (EngEx) is an NSF-funded ITEST (Innovative Technology Experiences for Students and Teachers) project led by UCAR SciEd that explored how middle school students from low-income families could engage in engineering after school to complement the science and engineering learning during the normal school day [1]. Our initial goal was to introduce a variety of engineering topics/platforms that related to the atmosphere and associated sciences including wind power, solar energy, aircraft design, atmospheric sensors, and testing physical models of dropsondes using a wind tunnel.

The project team collaborated with an after-school program near Boulder, Colorado, whose mission was to serve students from low-income families by offering multi-year programming to students and support for families. This group was initially interested in Engineering Experiences in order to provide STEM opportunities to their students.

In order to get to know the students and to get acclimated with the program, leadership, and students, the EngEx team tested some well-established activities common to many middle school engineering classes (i.e., designing and testing balsa wood gliders and wind-powered sail cars). These activities tied in nicely with our emphasis of platforms that can both carry instruments and study the Earth's atmosphere, but are also affected by the atmosphere. In informal feedback sessions, students in the program stated they wanted a more sophisticated/technical experience. When given various options for future programming, unmanned aerial vehicles (UAV) or drones were by far the most popular topic requested by students.

Based on the structure and attendance patterns of our partner after-school programs and the typical student attendance, we designed the lessons to meet these requirements. For example, since student attendance was inconsistent, we designed the lessons to be modular and self-contained. With the exception of the "learning to fly" series of lessons, students would not be required to have attended previous lessons in order to make sense of the current lesson. The lessons were also designed to be flexible with the amount of time required. While the lessons might ideally take 45 minutes to an hour, they could also be done in much shorter (30-40 minute) periods of time. Additionally, lessons were written to encourage active learning where students were out of their seats, flying drones, testing their performance or designing pieces to be attached to the drone to accomplish a purpose. While all of these approaches worked for the after-school environment, student learning was limited because of short exposure to the curriculum, the duration of time between sessions (typically a week), and inconsistent student attendance for the duration of the 10 weeks.

Table 1: Selected findings based on Version 1 of the EngEx Drone Curriculum

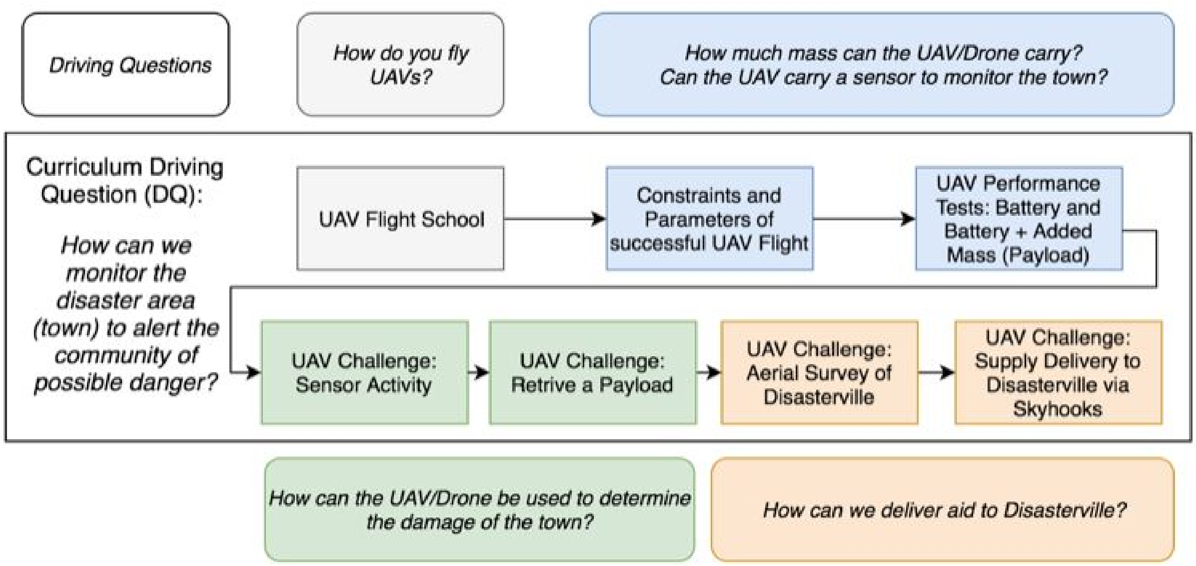
Positive Results	Recommendations for Improvement
Significant positive change in student affect and better understanding of engineering	Time allocated per week for the program is not enough for the students to get in-depth understanding of a topic
Participation of students in Engineering Experiences is mainly due to the content or the activities that the program offers	Including the Engineering Design concept into the curriculum is necessary for students to generalize their learning
Based on writing prompts, the curriculum on UAV (drones) was successful for students understanding positions and piloting the drone	Inconsistent participation or attendance limited student learning about engineering design

Over the course of two semesters we conducted two trials with this first version of the curriculum. The first cohort consisted of about 8-10 students who met once a week for about 30 minutes in the evening as part of their normal programming which included homework and recess. The second cohort consisted of about 40 students who met once a week on Saturday morning for about an hour. This second cohort also had a separate hour session on homework and enrichment activities that sometimes involved literacy, mathematics, and practical application/career connections related to the UAVs. Table 1 shows some of the findings based on research [2] conducted on Version 1 of the curriculum.

In Version 2, the developers found that a storyline-based approach [3] (Figure 1) was useful for youth to see how the individual lessons/skills build to address two overarching questions: "How can the UAV be used to determine the damage to a town?" and "How can we deliver aid to this town using UAVs?" We tested this second version again in two cohorts [4]. The first in an evening program comprised of about twelve students who had excellent attendance once a week over the course of the semester and the second cohort (about 100) who attended every day for three weeks in the summer.

We found that the storyline approach (Version 2) provided greater curricular coherence than the previous iteration (Version 1) of the curriculum where lessons were taught individually without the context of a driving question.

Figure 1: Engineering Experiences Storyline



In Figure 1, Version 2 of the curriculum, we started the unit with students considering a driving question concerning a disaster at a small town from the very beginning. While there was limited information about the town and the nature of the disaster, the intent was that students could learn how to fly the drone and learn about its capabilities through a deliberate sequenced series of lessons. For example, the first row in the storyline contains a series of “Flight School” lessons that teach novice pilots how to safely fly UAVs, an essential skill for all of the following lessons. After the “Flight School/First Flight”, lessons focus on measuring battery lifetime and determining the maximum payload weight that a UAV can carry. These activities include elements of both scientific measurement as well as some basic mathematical statistics. They also provide basic information about the performance limits of UAVs that is essential for answering the driving questions. In the second row of the storyline, students conduct two challenges. In the first challenge, students design and build a simple “skyhook” to attach to their UAVs to use to either pick up or drop off a payload. The second challenge requires students to “hack” the mounting of the camera on the UAV. Each of these challenges are described in detail below. The storyline approach provided a real-world context and reasons for students needing to learn the skills necessary to fly a drone and an understanding of the performance capabilities of the drone that were necessary for an aerial survey and subsequent rescue/aid to the town.

Skyhook: Engineering design challenge to retrieve a payload with a UAV

In the first engineering design challenge, “UAV Challenge: Retrieve a Payload” (https://scied.ucar.edu/activity/uav-challenge-retrieve-payload), students were challenged to design a method for their UAV to pick up a small payload and deliver it back to the UAV launch point. During the development of this activity, using a physical hook (a bent paperclip) in order to snag a package and bring it home proved much too difficult even for experienced pilots to accomplish. We settled on the use of a payload comprised of magnets, which while still challenging, was much more reasonable for novice pilots than other methods. We found that using a small neodymium magnet worked best, since they generate a much stronger magnetic force compared with traditional ceramic magnets. The magnet was embedded within a tiny cardboard box, which was labeled with a red cross to indicate that it could represent medical supplies.

Students were provided with craft materials (i.e., rubber bands, paperclips, string, washers, pipe cleaners, and tape) to create a skyhook that can be attached to the UAV that can then be used to retrieve a payload from across a large open space (gymnasium). We asked that students draw some initial ideas in their flight log/notebook and to compare their ideas with others before building the skyhook. We also asked them to hand test their skyhooks modeling the typical movement of their UAV to simulate an actual flight. Students were very creative in their designs. The only real limitations were that they should hang from the bottom of the UAV for safety purposes (away from the propeller) and any mass constraint that they learned about from the previous (Carry a Payload) activity.

Once students had conducted hand-tests and iteratively improved their skyhook designs, it was time for their small groups to choose the skyhook to test, mount it on the UAV, and conduct a real test in which they flew their UAV and skyhook together to retrieve the payload from one side of the gymnasium and return it back to the location of the team (working as the pilot, range safety officer, and spotter). For an added challenge, we used a stopwatch to time the retrieval effort. We also learned to have the students fly the UAV over a chair or other obstacle to prevent them from hovering along the floor to the payload location. Some of the ideas that students learned were about the skyhook (pros/cons of long or short) and the amount of 'swing' of longer hooks that hang from the UAV compared with hooks that are shorter and closer to the UAV, but are more susceptible to the 'back draft' of the air movement from the propellers as it gets closer to the floor. Other lessons learned include the decrease in responsiveness of the UAV controls based on skyhooks that are not balanced or are too heavy for the UAV.

Students were certainly excited when they successfully snagged a payload and returned it back to the group. Many were happy to keep repeating the retrieval over again to see how fast they could retrieve the payload. In our Version 2 of the curriculum we also designed about three lightweight skyhooks and printed them with a 3D printer. One of the designs was intentionally sub-optimal. The 3D printed skyhooks were easily attached to the UAV and the students used an augmented reality test (in place of the hand-tests) in order to decide which 3D printed skyhook to use during their actual trials with the UAV. One challenge that we needed to overcome with the 3D-printed skyhooks was the mass being a bit too large for the inexpensive UAV we were using. This made it more challenging to maneuver the UAV and difficult to be successful for the retrieval. We also used the 3D printed skyhooks to deliver payloads (i.e., small craft buckets) representing water following the aerial survey.

With an understanding of how to retrieve a payload, students were ready for an aerial survey of the disaster area in order to gain as much information as possible to plan a potential rescue/aid response for a town named 'Disasterville.'

Disasterville: Aerial survey of a disaster area

Our UAV curriculum includes a capstone challenge titled "Aerial Survey of a Disaster Area". To complete the challenge, students must conduct an aerial survey, using their UAVs with their cameras, of a model town that has been damaged by a natural disaster. The model town, dubbed "Disasterville", includes buildings made of blocks, toy cars, and figurines of people. Students cannot directly see the town; Disasterville is hidden from them by an intervening "mountain range" (a plastic tarp over some chairs). Students must fly their UAV over the mountain range, then hover above the damaged town while capturing video footage of the scene below.

Before their reconnaissance flight, students view photos of the town in its pristine, undamaged state. After their flight, students review the videos they shot, comparing the appearance of the damaged town with the "before" photos of the undamaged town. Using a visual checklist of the structures in Disasterville, students note which buildings were damaged and to what extent. They are also directed to look for injured people, crashed cars, and other signs of damage.

We chose a specific model of inexpensive, hobbyist-level UAV for this activity because that model includes a camera that streams video to a smartphone or tablet while the UAV is flying. Many inexpensive UAVs include cameras; but most record photos and videos onto a chip while flying, which can only be viewed after the UAV has landed. The UAV we used, the Syma X5HW, allows students to see a live feed from the camera while the UAV is flying and supports simultaneous recording of the video for later playback. Both features are helpful in this activity; students can tell via the live feed whether they are getting footage of all sections of the town while they are flying. However, the UAV is not a very stable platform, so the view tends to shift around quickly, making it very difficult to clearly discern the status of the buildings and other features in the town. Therefore, students must review their video recordings, pausing the video or replaying segments in order to get clear views of all sections of the town.

The activity also requires a bit of engineering design to mount the camera on the UAV for downward viewing. In the standard, "factory" configuration, the cameras on Syma UAVs are mounted in a fixed position, facing forward horizontally; they are not on a gimbal which allows the camera to be pointed separately from the UAV itself. In order to survey the town below the UAV while hovering above it, the camera must point downwards. A simple clip holds the camera on the UAV in the standard orientation, so it is possible to detach the camera from the aircraft and mount it facing downward. We supply students with tape and rubber bands and pipe cleaners to use to attach the camera to the UAV in a downward-facing orientation. The students must work within several constraints while "hacking" the mounting of their cameras: the electrical wire carrying power from the UAV to the camera is very short, restricting the possible mounting sites; the antenna on the camera for relaying footage forms a long "tail" on the camera that must not interfere with the UAVs rotors; and the overall shape of the camera makes is very difficult to mount directly under the aircraft's center, thus disturbing the balance of the vehicle when in flight. This last point is especially relevant, since the unbalanced UAV is challenging to control, making it very difficult to hover in stable flight while capturing videos. Students generally do not observe every feature in the town on a single flight. After reviewing their footage from an initial flight, students plan a second flight to capture footage of specific portions of the town they missed on the first try. This expectation that students usually will not get all the data they need on the first try reinforces the notion that iteration and persistence are key ingredients in the practice of engineering.

This capstone activity builds on and uses data from other, simpler activities conducted earlier in the UAV curriculum sequence. In order to plan their reconnaissance of Disasterville, students need to know how long their UAV can remain aloft and how it performs when carrying a payload (in this case, the camera). In one precursor activity, students simply test how long their UAV can fly on a single battery charge. This allows students to estimate the amount of time their UAV can spend hovering over Disasterville collecting video footage. During the battery test, students encounter simple statistical concepts, since different batteries and different aircraft generate different flight durations. Also, flying the UAV with a camera drains the battery more quickly, which the students discovered early on during their aerial survey flights. A second precursor activity challenges students to determine how much weight their UAV can carry, which helps them determine what payloads their UAV can fly with. Students first attach one small weight (we used metal washers) under the UAV and then rate the impairment of the UAV's ability to take off and to maneuver with the added mass. They repeat the process with two, then three, then more weights, up to the point that the UAV can no longer take off. Along the way, students noticed that the UAV became more difficult to control as the mass increased. Also, they often noted that control of the UAV can be severely reduced if the position of the weights is not centered under the UAV. In the Disasterville, scenario, both the amount of weight of the camera and its location influence the students' ability to get good video footage and to sustain the UAV's hover time over the town. This link between data and observations from the precursor activities to the capstone Disasterville activity is a key feature of the UAV curriculum, serving as an important "glue" to conceptually tie the activities together in students' minds.

The "story" aspect of the Disasterville scenario and the activities that lead up to it is an important feature of our UAV curriculum. On their own, simple engineering challenges such as the commonplace "build the tallest tower with toothpicks and glue", can be quite enriching. However, we believe that adding some level of storyline to the challenge can enhance the activity, providing context and making it more relevant to students. Measuring battery life and payload carrying capacity is much more interesting in the context of planning a mission to Disasterville. The Disasterville scenario also allows us to vary the type of disaster that afflicts the town; so far we have employed flooding, tornados, and volcanic eruptions. This flexibility allows the UAV curriculum to integrate with students' science lessons, so a teacher covering plate tectonics might smite Disasterville with a volcano, whereas a teacher covering the water cycle might unleash flooding.

The "story" aspect of the Disasterville activity is further extended by a follow-up literacy exercise. Students are challenged to conceptually design an aid mission to help the residents of Disasterville. The mission might involve delivery of medical supplies or food, medical evacuations of injured residents, or whatever other aid missions students can devise that employ a UAV. Students then write and illustrate a simple comic strip storyboard [5] that shows the elements and steps in their aid mission. The comic strips are required to include certain elements, such as a statement of the problem to be solved, the engineering design used to address the problem, the desired outcome, and so on. Providing context to engineering challenges in this fashion appears to make the activity seem more genuine to students, increases their sense of relevance, and makes the experience more memorable.

We discovered that the Disasterville activity, while very motivating to students, was also quite challenging. Since it was the first time students worked with the UAVs' cameras, there were technical hurdles to overcome to install the necessary app on SmartPhones and tablets and successfully sync up the apps with the UAV's. Students had to learn how the UAV handled while carrying a camera, and had to navigate more precisely than before to acquire good, stable aerial images. With later cohorts of students, we broke out some elements of the aerial survey activity into a precursor lesson about using the camera. Students took "selfie" pictures of themselves with the UAV's camera to practice using the camera, app, and wireless communication features. Next, they did simple, test survey flight over a single building from Disasterville that was in plain view (not hidden behind simulated mountains). This gave them practice with the precision flying required to hover over a target, and also showed them the quality of the video stream they would analyze in the Disasterville activity. These warm-up use-the-camera activities helped make the capstone Disasterville mission run more smoothly with later student cohorts.

UAV Mission Board Game

One of our main goals with the UAV curriculum was to have students explore the use of UAVs as airborne platforms for carrying atmospheric sensors. Scientists at our institution, the National Center for Atmospheric Research (NCAR), routinely monitor aspects of the atmosphere in situ at different heights using sensors carried by a variety of flying, falling, and floating aircraft (airplanes and jets, balloons, dropsondes, and UAVs). We wanted students to experience some sort of data collection and analysis activity using small, inexpensive sensors attached to their UAVs. We used small sensors (under 30 grams) that our hobbyist UAVs were just barely able to carry. However, all of our flying was conducted indoors to avoid issues with inclement weather and running afoul of FAA regulations. We tried to create artificial environments in parts of the gymnasium, using space heaters to raise the temperature and using humidifiers and boiling pots of water to generate humidity. Unfortunately, these approaches did not generate a strong enough local change to the temperature or humidity signal to be detectable by the UAV-borne sensor.

As an alternative lesson about UAV-carried sensors, we conducted a two-part activity in which we first had students carry simple sensors by hand to several locations inside and outside the school, then check the data for changes in temperature, humidity, and air pressure at the locations they visited. After this hands-on experience with sensors and data, we had students play a UAV Mission Board Game that we created for the lesson. The board game allows students to conduct an observing mission to a volcano using a “virtual” UAV. The game features tasks that encourage engineering optimization and iteration behaviors on the part of the students.

Our UAV Mission Board Game concept was inspired by two games created for NASA by Arizona State University: “Marsbound!” (https://marsed.asu.edu/lesson_plans/marsbound) and “Astrobiobound!” (https://marsed.mars.asu.edu/lesson-plans/astrobiobound). In each activity, students use a board game with cards to design a space mission, choosing between various options for launch vehicle, spacecraft power source, instruments, and so on. Cards represent equipment that students can add to their space mission, making decisions on which items to include based on cost, mass, energy requirements, and other factors.

In the UAV Mission Board Game, students are tasked with using a UAV to monitor a volcano near their town for signs of an impending eruption. To start, students receive $800 in pretend money to use to equip their UAV. They must buy at least one battery (from three options), at least one camera (so their aircraft can navigate), and optionally one or more sensors. Camera options include: an inexpensive, basic navigation camera; a high resolution camera; or an infrared camera. Sensor options include an infrared thermometer, humidity sensor, sulphur dioxide sensor, carbon dioxide sensor, and an aerosol sensor. A game card for each object lists its cost and mass, plus additional factors relevant to the type of object. The three battery options each list the charge capacity for that battery. Each camera and sensor includes a “Science Data Points” (SDP) value, which is the main way that scoring and success in the game is measured. In general, instruments that are more expensive and/or heavier also have the highest SDP values. Students must balance weight, cost, and science data considerations as they equip their UAV, essentially conducting an engineering optimization approach to setting up their aircraft. Students place the equipment they purchased in appropriate slots on a game board that represents their UAV.

After they equip their UAV, students turn their attention to a second game board to conduct their virtual flight to the volcano. The mission board has a series of spaces representing home base where the UAV takes off and lands, the nearby volcano looming over the town, and a series of spaces representing one-minute intervals along the 5-minute flight to the volcano. During each minute the UAV spends hovering over the volcano, students collect Science Data Points based on the combined SDP values of the instruments and cameras mounted on their UAV. The total number of SDPs students collect over the course of three flights represents their overall score in the game. The specific battery model students equip their UAV with, and the overall weight of the UAV with its payload of cameras and instruments, determine how long the UAV can remain airborne. Heavier UAVs loaded with sensors discharge batteries more quickly, limiting the amount of time the UAV can spend at the volcano collecting science data. This presents students with another optimization problem: balancing the amount of science data that can be acquired each minute by a full suite of sensors against the desire to hover at the volcano for several minutes collecting data by employing a lightweight UAV configuration with fewer sensors that drains its battery more slowly.

After each flight, student teams earn extra in-game cash depending on the amount of science data their previous flight collected. Between flights, students can reconfigure their UAV with a different set of instruments, cameras, and battery. They can adjust their prior configuration, adding more sensors or cameras to increase the per minute science data collection rate; or lightening the load to produce a longer stay at the volcano. They can buy more expensive and capable instruments with their extra cash. As students adjust their UAV's configuration between flights, they engage in an iterative design process, thus learning more about the practice of engineering.

Two types of "event" cards add some randomness and hence variability to game play. Each minute the UAV is airborne, whether en route to or from the volcano OR while hovering over the volcano, students draw a "flight event" card. Cards include headwinds that cause accelerated battery depletion, instrument malfunction cards that reduce science data collection, and a range of other mostly-bad things that can happen when a UAV is airborne. We were pleased to observe several students, after having experienced all of the things that could go awry when they were flying actual UAVs, comment on how the troublesome flight events in the board game seemed realistic as compared with their own experiences while flying physical UAVs. The randomization effect that the flight event cards add to the game forces players to encounter another engineering concept, the notion of margin of safety. Students cannot perfectly predict the battery charge duration, and hence the total available flight time, for their UAVs, since the flight event cards alter this total depending on which cards are randomly drawn. To deal with this uncertainty, students must account for a reasonable amount of "bad luck" associated with flight event cards in determining how long they can remain at the volcano collecting data before heading back to base.

A second type of randomly drawn card influences the science data collection aspect of the game. During each minute the UAV hovers above the volcano, students draw a "science event" card. These cards provide a bonus to the science data points collected if they correspond to an instrument the UAV is equipped with. For example, students might draw a carbon dioxide emissions science event card, which would give them extra science data points if their UAV was equipped with a carbon dioxide sensor. The rationale for this feature is that certain vents on the volcano might be strongly emitting carbon dioxide, but the UAV could only detect that if it was carrying the relevant sensor. This aspect of the game encourages students to equip their UAVs with a variety of sensors, to be most likely to gain extra SDPs across a range of randomly drawn science event cards. Once again, this encouraged optimization discussions; more sensors weigh more and produce shorter flights, but collect more SDPs per minute and have a greater likelihood of corresponding to a science event card point bonus.

Overall, our goal with the board game was to give students some of the experiences, and especially engage in the kinds of thought processes used by engineers, that they would have had if they were able to fly a larger, more expensive UAV that was capable of carrying sensors and that was flown outdoors where there would be conditions to sense. Based on observations of student behaviors, we believe the game has been a success. We definitely observed, in different student groups at different sites, much discussion among students about 1) the choices they needed to make and factors they needed to balance as they equipped their UAVs, and 2) how to change their configuration and tactics from one flight to the next. We were concerned that student motivation would be poor when students were told that they would be sitting and playing a game instead of flying their drones today, but found that students quickly became very engaged and enthusiastic as they played the game. We noted numerous instances when students compared their experiences with actual, physical UAVs to the situations and rules within the game. One student generated some clever outside-the-box thinking by proposing to hover over the volcano for as long as possible on the third and final flight, collecting data until the battery was depleted, and intentionally crashing the UAV into the volcano. Initially, we thought to disallow this attempt to take advantage of a loophole in the rules (there are penalties, though rather mild, for running out of power and crashing before making it back to base). However, after some discussion with students, we realized that this approach could be viewed as completely reasonable in some real-world situations, and thus allowed it in the game. Our reasoning was that the town's inhabitants might be very willing to sacrifice a thousand-dollar UAV if it provided crucial, timely, and potentially life-saving data about an imminent eruption.

We are investigating the possibility of making an immersive, computer-based version of the game, possibly in a virtual reality (VR) setting. The VR version will retain the equipment selection and optimization features from the board game that serve as the most essential, central "learning engineering" aspects of the game. It will enhance the experience by including a UAV flight simulator, which replaces the mission board in the board game. Instead of moving tokens at one-minute intervals on the board, players will fly their virtual UAV using joystick controls almost identical to those employed with physical UAVs. Performance of the UAV in the flight simulator will be affected by the instrument payload weight, factors such as strong winds, and so on. The board game served as an excellent paper prototype for the VR game, allowing us to test the concept with students and revise the rules and features before starting software development for the VR version.

Lessons learned and recommendations

Over the course of the Engineering Experiences project, we learned several lessons about working with UAVs in an educational setting and about implementing engineering education in an outside of school-time (OST) environment.

All of the UAV flying in our program was done indoors; often in a gymnasium, but also in a cafeteria or other large, multi-purpose room with a fairly high ceiling. Inexpensive, hobbyist UAVs fair poorly in any wind stronger than a light breeze. Flying indoors allowed us to avoid problems with windy days, as well as other adverse weather such as rain or snow. Flying indoors also avoided dealing with FAA regulations, including proximity to airports, and also prevented any conflict with the schools' neighbors if errant UAVs were to accidentally fly away from school property. Indoor flying spaces must be checked for fragile obstacles suspended from the ceiling, such as light fixtures, projectors, or fire sprinkler systems that could be set off by being hit by a UAV. Since gymnasia are designed with protective covers, that can withstand balls, over clocks and similar items, they are especially well-suited to safe UAV flying. A typical gymnasium readily supports use by 15-20 students at a time, with groups of 4-5 students per UAV each working in one of the four corners of the gym.

It is important to have plenty of extra batteries on hand for the UAVs, since battery recharging time (about an hour) is far longer than the time required to drain a battery's charge (10 minutes or less when flying). We found the UAVs we used to be remarkably durable and it is crucial to have spare parts (especially propellers) on hand for quick repairs. Crashes are inevitable with students who are learning to pilot, so it is wise to allow time for repair work, recalibration, and quick test flights to verify that aircraft are flying properly after adjustments and repairs.

The low-cost UAVs (about $50) we used had advantages and limitations. They were sufficiently inexpensive to allow us to have plenty of aircraft for students, including spares to quickly swap in and keep the lesson flowing if one UAV developed problems. Inexpensive UAVs were not intimidating to students, and made the frequent crash landings that occurred while students were learning to pilot "no big deal". However, these lightweight UAVs could not lift very much weight, largely disrupting our plans to fly sensors on the aircraft. In our program, we got around this hurdle by having students play the UAV Mission Board Game to gain some experience with aspects of sensors onboard UAVs. An alternative solution that could be used with smaller groups, such as an after-school club with a few students, would be to buy fewer, more expensive UAVs that are capable of carrying heavier payloads of sensors.

In the second version of the curriculum, we emphasized the storyline of using UAVs in disaster relief as a glue to conceptually link together the series of activities in the curriculum. For example, activities for measuring the battery lifetime or the amount of payload the UAV could haul were presented in the context of planning for the upcoming survey and relief flights to Disasterville. This seemed to satisfy students' needs to know "why we're doing this" and to motivate their engagement with the precursor activities. We did find that we needed to emphasize these connections and make them explicit for students, especially the cohorts that only met once each week.

Finally, logistics related to scheduling and attendance can have a strong influence on the success of a program. Attendance at after-school programs can be very irregular. We initially tried to accommodate student absences by making each lesson as standalone as possible, though this wasn't possible with some of the crucial prerequisite learn-to-fly lessons. As we discovered the importance of using the disaster relief storyline to motivate students and tie together the activities they were experiencing, we had to balance the effectiveness of that approach with students who had missed one or more sessions and were not entirely up-to-speed with the storyline. Also, the after-school timeframe may be an especially challenging time to attempt to entice students to be enthused about an intellectually-demanding topic such as engineering. Students in our after-school cohorts were often visibly tired, both physically and mentally, by the time they encountered the Engineering Experiences curriculum. Their other options for activities during the after-school program, which our curriculum was in some ways competing with, tended to be physical activities such as sports or meditation or other activities that were less mentally taxing that the UAV curriculum. In an after-school timeframe, those mentally less-demanding activities may be more appropriate for students than engineering lessons, even fun and active ones involving UAVs. For comparison, our cohorts that met on Saturday mornings or during the summer were clearly visibly more fresh and seemed much less mentally fatigued. No matter when we met with students, the duration of the meeting time also seemed an important factor. As is generally the case with hands-on activities, we found that setup and troubleshooting and other aspects of dealing with supplies and technology inevitably cut into the overall time allotted for each activity. In our early cohorts, our meeting time was ostensibly slightly less than an hour, which generally was closer to 40 minutes by the time all students arrived and were settled in. Although this was okay for some sessions, other activities were very rushed and much less effective due to the time crunch. With later cohorts we insisted on a time slot closer to an hour-and-a-half in length, which led to much better results, even in an after-school setting.

Although there were many challenges to engaging students with engineering activities using UAVs, the Engineering Experiences project was successful at providing students with a highly motivating learning experience. Students, facilitators, and program coordinators at each of five sites with different cohorts reported that the program provided a positive experience. Interviews with students revealed that they entered the program thinking of drones as toys, but after the experience viewed them as tools. We conclude that UAVs can be used as a means to provide opportunities for learning engineering that are both highly motivating AND academically rigorous.

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