Training to Understand, Diagnose, Adapt, and Repair Electromechanical Systems

Mr. Srujal Patel, Georgia Institute of Technology

Mr. Srujal Patel serves as the research faculty at Guggenheim School of Aerospace Engineering (AE) at Georgia Institute of Technology. Mr. Patel earned his dual M.S. degrees in Aerospace Engineering and Applied Mathematics at Georgia Tech with specialization in Applied Numerical Analysis and Computational Fluid Dynamics/Aerodynamics. After joining as the research faculty, Mr. Patel worked as project manager for the Manufacturing Experimentation and Outreach (MENTOR) program - an initiative aimed at introducing new design tools and collaborative practices of making to high school students across the United States - sponsored by Defense Advanced Research Projects Agency (DARPA). Mr. Patel has also served as Project Manager for DARPA's MENTOR2 program which involved developing project kits and curricula to train the U.S. armed forces to understand, troubleshoot, repair and adapt electromechanical systems. Mr. Patel also teaches courses in Systems Engineering, Aerodynamics and Digital Design & Manufacturing at School of AE at Georgia Tech. Currently, Mr. Patel is working as the Project Manager for Innovative Mars Exploration Education and Technology (IMEET) program - funded under NASA's CP4SMPVC+ grant – in which Georgia Tech is developing curriculum and project kits that will be used during the summer camps to be run at partnering Informal Education Institutes.

Dr. Maria-Isabel Carnasciali, University of New Haven

Maria-Isabel Carnasciali is an Associate Professor of Mechanical Engineering at the Tagliatela College of Engineering, University of New Haven, CT. She obtained her Ph.D. in Mechanical Engineering from Georgia Tech in 2008. She received her Bachelors of Engineering from MIT in 2000. Her research focuses on the nontraditional engineering student – understanding their motivations, identity development, and impact of prior engineering-related experiences. Her work dwells into learning in informal settings such as summer camps, military experiences, and extra-curricular activities. Other research interests involve validation of CFD models for aerospace applications as well as optimizing efficiency of thermal-fluid systems.

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Introduction

All electromechanical systems have a limited scope and a fixed lifespan. It is inevitable that at some stage the operators will be required to either adapt a system to satisfy its new requirements or diagnose, troubleshoot and repair in case of faults/failures. Such tasks require that operators and technicians are, not only prepared to know how to successfully identify the requirements of a broad range of systems on hand, but also to have the ability to provide innovative solutions using limited replacements and/or fabrication resources available in low-technology austere environments; for example, for Army or Navy on-field missions, the long logistical supply chains challenge the ability to obtain spare parts in a timely manner and technicians are required to maintain and adapt systems in short time-frame, especially if the systems are mission critical.

This paper describes how one can utilize a hands-on pedagogical approach to teach universal principles on which all moderate to highly complex electromechanical systems work. The curriculum, developed using exemplary project kit, provided learners basic foundation and then introduced them to a systematic and all-encompassing process to diagnose, troubleshoot and adapt a broad range of electromechanical systems. A quadcopter was chosen as the exemplary project kit to teach the concepts. A non-linear learning platform was developed to enable learners with various technical backgrounds to learn the information in as efficient manner as possible. After learners were familiar with the system, a variety of failures were introduced in the system and learners were required to diagnose and repair the quadcopter using a systematic process which enabled them to acquire the skills to utilize a broad set of tools and technologies, a subset of which could be available in real-life situations. The curriculum also enabled learners to adapt such systems using pre-existing components of other systems, through manufacture of as-designed components or through the design and manufacture of new components using additive manufacturing technologies.

The following sections include an overview of the development and implementation of course curriculum and the computer-based learning platform. The data presented are based on two workshops taught to military personnel. These workshops served as a case-study and provided valuable feedback on the pedagogical approach, the learning platform, and curriculum modules. The paper concludes with suggestions for modifications and future applications.

Background

This work was sponsored by Defense Advanced Research Project Agency (DARPA) under Manufacturing Experimentation and Outreach 2 (MENTOR2) program [1]. The program was divided into four focus areas, and work was assigned to multiple contractors by assigning them to one or multiple areas. Our team, henceforth will be referenced as CREATE team, was awarded to perform under two of the four focus areas, which are detailed below with their primary objective.

Project Kits and MOOC Materials: Under this focus area, performers were asked to develop open-source experimental kits for a small number of exemplary projects that provide materials and guidance, link to previous math and science fundamentals, and allow for individual creative freedom and diverse talents to be exploited in the design and construction of authentic problem-based projects related to understand.

Demonstrations and Evaluations: Under this focus area, performers were asked to develop a demonstration and test plan that allows for the evaluation of the methods, tools and materials being developed in Focus Areas 1, 2, and 3. The demonstrations were to be carried out at a defense training facility and/or a civilian training facility (e.g., vocational technical school) and/or a non-traditional learning environment (e.g., a Makerspace).

Curriculum

The curriculum is divided into two main sections: 1) electromechanical systems-specific modules which taught core concepts, and 2) quadcopter kit-specific modules which taught how to use those concepts for a particular system's build and repair. Table 1 describes modules and the subtopics within each section.

Table 1. Curriculum sections and modules within each section

Electromechanical systems-specific modules	**Quadcopter kit-specific modules**
Circuits: Understanding Circuits, Parallel & Series Circuits Power basics: AC & DC Power Multi-meter: Power, Current, Voltage measurement Electric Motors: How motors work, applications, Motor types, Brushless DC Motors Signals & Frequency: Signal Terminology, Analog vs Digital Signals, Duty Cycle Pulse Width Modulation: how Electronic Speed Controller (ESC) works Feedback Control: Open loop controller vs feedback Controller basics Proportional-Integral-Derivative (PID) controllers and PID Control Tuning: States, Errors, Tuning the gains Troubleshooting basics: Troubleshooting flowchart, how to use Oscilloscope, Multi-meter, Servo tester	Quadcopter basics: How quadcopters work, main components, quadcopter assembly configurations Propellers basics: How propellers work, aerodynamics terminology, different configurations Soldering: Basics, how to solder a connector onto a wire on a quadcopter, soldering a circuit board Quadcopter assembly: How to assemble all components of quadcopter together Battery Basics: How batteries work, Lithium Polymer batteries, how to test battery voltage Control Board basics: How control board works, how to wire the control board with all other electrical components Transmitter and Receiver: How each of the component works, Transmitter modes Quadcopter Operations and Safety: How to fly a quadcopter safely, precautions and standard operating procedures

Pedagogy

The curriculum developed is self-contained, self-paced and is intended to train military personnel without an on-site instructor; allowing them to learn without any time or location constraints. To keep the learners engaged, we sought for a non-linear content delivery platform so that the learners would choose a course map that would fit their needs and prior experience in using and troubleshooting electromechanical systems.

The CREATE team evaluated existing Massive Open Online Course (MOOC) platforms [2, 3, 4, 5, 6] where the training content could reside, upon which it was concluded that none of the existing platforms could meet the desire for a non-linear learning. Each of the existing platforms were designed to progress a learner through a series of sequential lectures, and didn't serve well the desire to allow learners to explore the topic areas and able to switch from one topic to other in an order that best suited them. Also, the military training meant that there was considerable value in ensuring that the videos and associated material could be accessed with limited internet connectivity. Thus, the CREATE team made the decision to develop an independent computer-based learning platform using WordPress [7] which could be accessed online or off-line on a computer using any standard web-browser. Multiple studies have shown that video-based learning helps the learners with attention as well as retention compared to traditional text-based learning [8, 9, 10]. The CREATE team produced a series of short video lectures (Figure 1) which contained just enough information on electromechanical systems to remove the perception of those as "black boxes". Such videos are often found among Do-It-Yourself (DIY) communities and makerspace websites. The topics are presented in an order of increasing complexity, with some topics requiring knowledge of previous topics. For example, the video lectures on motor types requires an understanding of direct and alternating current. However, learners can start with more challenging topics and work backwards when they need to review any topic if they desire. Upon selecting a video lecture topic, learners are given the option to either move directly to the video lecture and other learning content, or they can select to go to "*try your knowledge first*" section which takes them to an optional pre-quiz which is intended to provide the learners feedback on their understanding of the topics covered in the section.

Figure 1. Video map on the non-linear web-portal

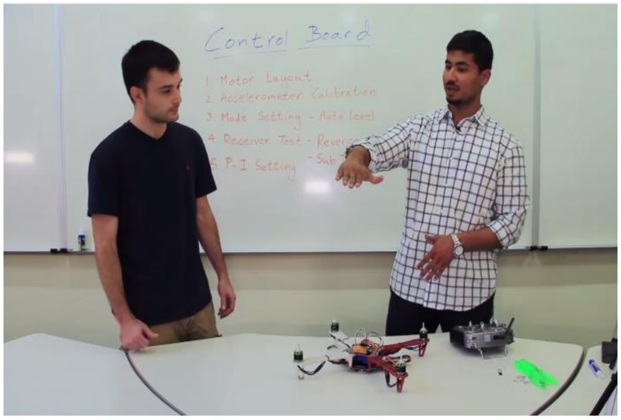

Figure 2. Example of a conversation style video lecture

After completing the pre-quiz, learners are directed to the lecture content. The team experimented with multiple formats for delivering the video lectures, ranging from fully animated, to the recording of a whiteboard style lecture. The team determined that two actors (Figure 2) having a conversation on the topic was the most effective means of delivering the information. These conversation style lectures were interspersed with animations and demonstrations, and a paired discussion in front of a whiteboard.

Alongside of the video, each webpage contains a color-coded set of *Highlights* which help the learners remember key concepts, safety information and provide a reference when it becomes necessary in completing the kit build. For several topics, the text based content is supplemented by interactive elements of the webpage (Fig. 3) that allows the learner to examine the topic as an active participant and lets the learner explore without the hesitation that may come from a fear of breaking the equipment or sustaining an injury.

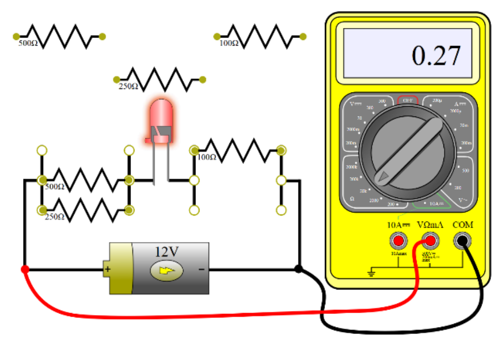

Figure 3. Example of interactive tools: Depending on different multi-meter and resistor configurations multimeter will display appropriate measurements

To supplement the learning material, the platform contains a list of relevant links to other useful training materials. Finally, each module contains an optional post quiz, so that learners can determine if they have retained key elements of the topic.

Evaluation: Workshops

Two workshops or demonstrations were carried out at military facilities to evaluate the training material developed. The evaluation instruments developed were formative and summative in nature. The formative evaluation questions probed how effective, efficient, and engaging the curricula/tools were in meeting their objectives. The summative questions measured overall success of the demonstrations in meeting the objectives set forth by DARPA. The evaluation instruments were approved by Georgia Tech’s Internal Review Board (IRB) and DoD Human Research Protection Office. The evaluation instruments can be divided in four different survey categories.

1. Registration Survey: to collect the background information and prior exposure;

2. Pre-surveys and Post-surveys for each performer's workshop: contained approximately twenty questions specific to the curriculum of each workshop; additional feedback questions were added to the post-surveys.

3. Surveys for the workshop facilitators: These surveys were geared towards assessing the effectiveness of the curriculum and instructional methods from workshop facilitators' perspective.

4. Focus group questionnaire: A focus group collects qualitative data via a semi-structured group interview and results are reported in aggregate.

The two workshops conducted by the GT CREATE team were geared towards promoting how to build, diagnose and troubleshoot an electromechanical system. The details of the workshop agenda are listed in Appendix A.

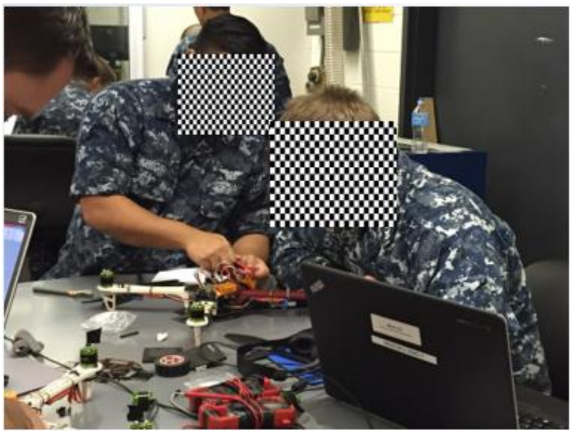

Figure 4. Participants at MARMC working on the quadcopter kit

The workshop participants were asked to follow the self-paced course on the web portal to build the quadcopter using as many lectures as they need to learn the core concepts. Once the kits were assembled and tested, participants were required to solve the diagnostics and repair challenge. In this challenge, multiple failures were introduced by the workshop facilitators, and the participants were then required to diagnose and repair all the failures (non-working electrical components, broken/incorrect wiring, incorrect propeller assembly etc.) within the timeframe of 3 hours.

Additionally, to evaluate the participants' understanding, they were asked to increase the capability of the baseline system requiring them to modify the electronics and rapid-manufacturing based hardware. For example, one team was asked to adapt the baseline quadcopter into a hexcopter in order to lift more payload; the finished build of the hexcopter (Figure 5). Participants were allowed to use a laser cutter machine to print the quadcopter frame components.

Figure 5. Adapt challenge: Building a hexcopter using laser cut assembly board

Participants

Information was collected using the registration survey to provide insights into the participants. Fig. 6 provides an overview of who was involved at each workshop; it is noted that because of the limited number of responses the information is presented in aggregate to preserve the anonymity of the individuals. A total of 12 participants took part in workshop 1, and 8 participants in workshop 2.

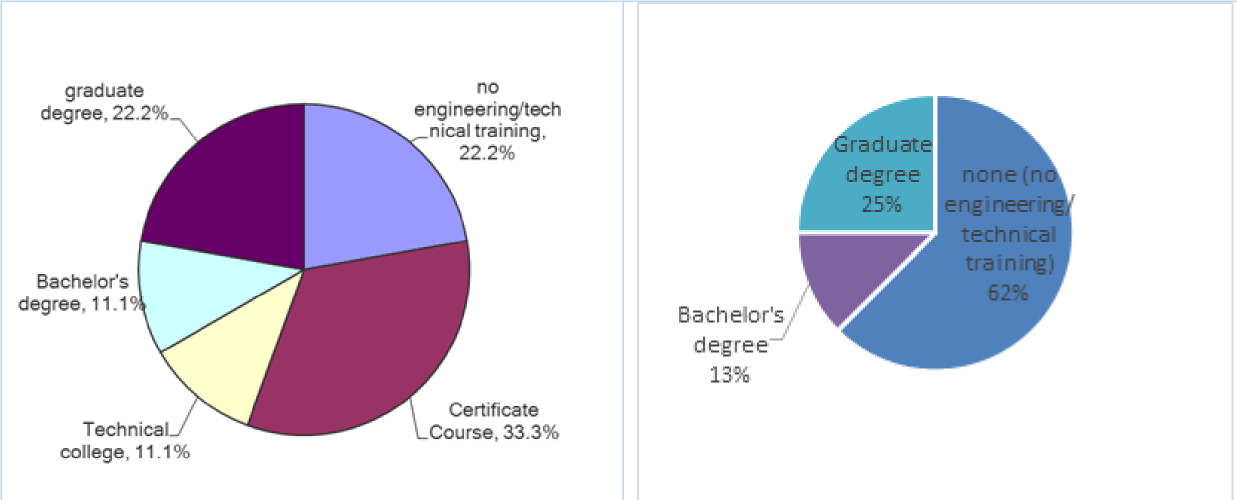

Figure 6. Breakdown of Participants' Education; Left – at MARMC; Right – at SOCOM

For workshop 1, when asked if they had *experience with quadcopters*, only two reported having flown commercially-available versions; the others reported no experience in troubleshooting or building a quadcopter. A follow-up question asked how many hours a week they each spent maintaining/troubleshooting electromechanical systems. Of those responding to the question, two stated *5-10hrs*, four stated *1-4hrs*, and four participants stated *0 hrs*. It is worth noting that no one selected *more than 10hrs*, highlighting the fact that out of the participants who responded to the question, none have job directly related to handling electromechanical systems.

For workshop 2, participants were asked if they had experience with building and operating quadcopters/3D printers. Majority had never built any, however 75% had experience in operating pre-built drones and 3D printers. Based on open ended statements, it is clear that participants at this workshop were more hands-on with electronics/electromechanical systems which required some knowledge of circuits.

Pre/Post Survey: Concept Questions

For workshop 1, the answers Pre/Post survey multiple-choice questions show a trend of improvement in understanding of the concepts after the workshop (Appendix B). The multiple-choice questions were mainly focused on concepts on basics of electricity, circuits, motors, and quadcopters. From the results, we concluded that even though concepts in circuits, motors and quadcopters had shown positive trend (18 out of 23 questions), answers to electricity-related questions did not show an improvement. There could be several reasons: a) Since the videos were viewed at the participants' discretion, they skipped the basics videos because they were assumed to be not relevant and hence students never learned the concepts 2. The concepts were not properly explained in the video. 3. Interestingly, all the questions which had poor performance required use of some form of an equation, so participants did not remember the equations at the end of the workshop.

For workshop 2, the pre/post surveys were modified to be open-ended but still focused on concepts on basics of electricity, circuits, motors, and quadcopters. Based on the responses, the students were "graded" in four areas, understanding of systems at hand, understanding of technical issue, approach of diagnosing the issue, and understanding on how to fix the issue. The "grading" use a rating from 1 to 5, with 1 being *does not understand concepts, no exposure to concepts before*, and 5 being *Exceptional understanding, should be able to translate to other systems of advanced complexity.* The results are summarized in Appendix C. We observed that two out of eight participants already had advanced level of skills in dealing with electromechanical systems, while there were two participants who had no prior background, who did show improvement in their understanding in all four categories.

Pre/Post Survey: Satisfaction Questions

Each of the post surveys included a set of questions to gauge individual satisfaction with the activities of that particular workshop. From the responses, it is clear that participants enjoyed the workshop with 70% - 80% of the responses being *strongly agree.* There was also strong agreement that, because of participation in these workshops, the individuals would like to participate in this type of program again. Most of the participants found the information *interesting* to them. When asked if the information in the workshops would be useful to them over 80% of them replied *agree* or *strongly agree.*

Participants indicate a desire to learn more about *electromechanical systems* with six of them *agreeing* or *strongly agreeing.* Five of the participants would like to learn more about *quadcopters;* however, three state no interest in learning further about them. Regarding *diagnostics & repair techniques,* there was no consistent reply and responses ranged from strongly agreed to strongly disagreed to learning further about the techniques. Similarly, the question regarding *online learning environments* resulted in four participants expressing desire to learn more about this format, while three disagreed and three participants remained neutral.

At workshop 2, the majority of participants indicated that they were confident they would be able to perform these functions with good confidence after taking this workshop. Also, considering that many of the participants would have advanced skillset in such tasks before the workshop, we asked them how would they compare the knowledge before and after. All 8 participants suggested that their understanding improved somewhat or greatly improved in learning how to correctly diagnose a problem and/or determine an appropriate repair. Except one participant, all other agreed that their ability to successfully implement repair also improved. All participants agreed that their skill level improved in area of redesign or adaptation of small electromechanical systems.

Facilitator's Notes

In both workshops, the facilitators’ notes yield insight into participants’ rank and team dynamics. Information regarding ranking order or specifics of the participants’ occupations could not be collected because of restrictions put in place by IRB approval; the number of participants was too low to ensure anonymity if such identifying information were to be collected. In general, the comments from the facilitators reveal that the participants were highly engaged, willing to try multiple tasks and iterations. The comments are summarized in Appendix D.

Focus Group Discussions

The first part of the focus group discussion was concerning the participants' motivation to take part in the workshops. At workshop 1, reasons were across the board. Some participants said that they were interested in learning more about additive manufacturing, some said building quadcopters was something that caught their eye, and some said participating in an event that was conducted by "MIT, Georgia Tech and Stanford folks" was really attractive.

The participants were asked about their overall experience of the workshop curriculum as well as the teaching methods used. In order to understand the efficiency of the eLearning model, the students were asked to strictly follow the videos to learn the content and when student asked any questions, instructors redirected the students to a video that could answer that question. If the question was not answered by any videos on the website, students were given appropriate instructions and the instructors made note of the gaps so that they could be improved in the future. Overall, workshop 1 participants appreciated the eLearning model, for instance, one participant directly stated:

> *"Trying to just use videos was extremely frustrating at first, but in the end when I could build the quadcopter and troubleshoot it without any instructors' help; there was a sense of accomplishment and overall it made the experience rewarding."*

Overall, consensus in the workshop 1 group was that they enjoyed participating in the workshop and learned a lot. All participants agreed that the interactive nature of the workshops was the most impressive and enjoyable feature. One participant summarized by saying:

> "I really liked the fact that there were very few to no PowerPoint slides [...] workshops. That kept me engaged through out."

When the participants were asked to comment on their views on the duration of the workshop, they said:

> *"I think everybody was really engaged in learning the material and so I don't think we felt that eight hour/day for total five days of the training was an issue."*

However, all participants agreed that they would have preferred more depth in the workshop curricula. One participant suggested that in the future if some participants lacked the basic background necessary to learn more advanced concepts, they can go over the introductory tutorials ahead of time before the workshops begin.

Finally, we asked the participants whether any technology or content they learned could be applied to their daily job. Their answers varied from applications at MARMC to applications in austere environments, for example, while sailing.

> *"If the technology is available on ships, viewing videos (visual information) to understand and repair any systems would be very helpful. However, for the Fab*

workshop, instructor participation was necessary, the self-paced format would have taken way too long."

The focus group for workshop 2 involved all 8 participants. They were eager to share their comments and spoke highly of their experience during the week. Overall, they found the exercises challenging and a good use of their time.

The participants stated that the online modules did provide the content needed for the task at hand. They commented on the level and suggested that the online format provide guidance as to where to start depending on the individual's background.

However, they strongly felt that the presence or access to an instructor was instrumental in their success. Comment included statements such as:

> · *"everyone learns differently … and instructor can adapt and a computer can't; the instructor can ensure that people don't get stuck and don't give up and that there is a little less frustration … there needs to be frustration because I think that frustration helps the learning process"*

> · *"… we had some instances where we built the quadcopters and they worked just find and then [instructor] provided an additional challenge so we kept on learning – without [him] we would have done the barebones"*

When asked if they had learned skills or information that would be applicable to their day-to-day, this participant's comment captures the sentiment well:

> · *"for this course for me, on the electronics and programming side … I thought it was rocket science … but getting that exposure makes me feel like, it has taken the mystique off it, where I am not as intimidated and I can look for resources, look it up on the internet, program them into a circuit card, solder the wires that previously I wouldn't have been comfortable doing but now I am"*

When asked about getting others to use the training materials they expressed that they did foresee others wanting to access content such as what was presented in the workshop. They suggested that organized workshops would work best – with wider reaching advertising so that more individuals are aware. When asked directly if they would recommend the training materials (and workshops) to others including individuals that may work for them – there seemed to be consensus of *yes* they would.

The conversation wrapped up with comments regarding the type of training and would they foresee it as helping them (or others) to develop skills to maintain, adapt, and repair a system in austere environments. The group expressed that the material is a great way to introduce new concepts to an individual and as a result would lead to improved broader skillset. They expressed that the material served as a *primer* to instigate interest in learning more. Statements such as:

> · *"If you really want people to get the most out of this, don't let them go to their comfort zone. In other words, if you have a guy who is a computer programmer in his day job*

don't have him do the code on the project; make him cut the stuff on the laser cutter; and don't have the electrical engineer build the circuit … have him do the mechanical stuff."

· *"to some level yes, this is getting people more informed and capable to do; - but it will depend on the level, depending on how complex the system is, and no matter what your environment is, if you aren't already knowledgeable about and have the expertise on that system – you aren't going to be able to completely fix and troubleshoot it just because you went through one of these [workshops]"*

Conclusions

Early testing with the course content material has demonstrated the validity of the chosen approach in providing self-paced learning to understand, build, repair and adapt electromechanical systems in austere environments. Learners who have used the course have been able to successfully build and fly a quad-rotor UAV without input from a teacher. Upon discussion after completing the activity, the learners seemed to have retained a large amount of information on electromechanical systems. The demonstrations were conducted at military facilities and the data collection involved use of formative and summative evaluation instruments including Registration Surveys, Pre/Post Surveys, Facilitators' surveys, Satisfaction Surveys, and Focus group sessions. The pre/post surveys provided evidence of effectiveness while showing that there is still room for improvement. Facilitators' observations emphasized the users' engagement and provided rich data for items to address and improve for the workshops and broader dissemination of the content in the future. The participants' satisfaction surveys as well as information collected at the focus group session reveal a consensus that the content used during the demonstrations would indeed be relevant to military personnel in their daily activities. Despite the limited sample size, we believe demonstrations were not only successful in achieving the goal of aiding the developers with the valuable feedback in improving the tools before broader dissemination, but also, they provided insights into the usability and utility of the tools, technologies and curricula developed by the performers.

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Appendix A

Table A1. Agenda for Workshops 1

Module Name	Module Description	Duration
Overview	Demonstration of quadcopter, overview of the website, Introduction to the pedagogical approach	1 hr.
Introduction to mini-kit	Online course on how electric circuits work using a mini-kit consisting of motor kit, consisting of a battery, motor, speed controller, and servo tester	1 hr.
Introduction to Quadcopter Kit	Online course on about quadcopter components and step-by-step instructions on how to assemble it. Objective is to develop some basic know-how with assembling circuits and mechanical parts, and build confidence in working with these systems.	3 hrs.
Hands-on experiments	Online Lectures with small kit experiments interspersed to give a break from watching the videos and to provide demonstrations of concepts. Experiments include: □ Spinning up the motors, changing the controller inputs to vary the speed and direction □ Flipping the +/- wiring to observe direction change of the motor spin □ Measuring the voltage/amperage at different points in the setup □ Using an oscilloscope to visualize the signals □ Possibility an activity corresponding to lift and controls □ The final activity is the first quadcopter flight	3 hrs.
Troubleshoot and repair challenge	Failures are introduced in the quadcopters in one or more ways and students are required to troubleshoot and repair the quadcopter to its original functionality. Potential failure include: □ Break a motor (replace a motor with a broken one) □ Reverse wiring □ Damaged control board □ Break a propeller □ Dead battery	3 hrs.

Table A2. Agenda for Workshops 2, Quadcopter Module

Module Name	Module Description	Duration
Overview	Demonstration of quadcopter, overview of the website, Introduction to the pedagogical approach	1 hr.
Introduction to mini-kit	Online course on how electric circuits work using a mini- kit consisting of motor kit, consisting of a battery, motor, speed controller, and servo tester	2 hr.
Introduction to Quadcopter Kit	Online course about quadcopter components and step- by-step instructions on how to assemble it. Objective is to develop some basic know-how with assembling circuits and mechanical parts, and build confidence in working with these systems.	8 hrs.
Introduction to 3D Printer Kit	Online Course about 3D printing components and then step-by-step instructions on how to assemble it. Instructions for 3D printer calibration are taught in separate video as well. After students successfully build and calibrate the 3D printer, a video on how to troubleshoot the printer guides them through a systematic process of diagnostics and repair of the	8 hrs.
Hands-on experiments	Online Lectures with small kit experiments interspersed to give a break from watching the videos and to provide demonstrations of concepts. Experiments include: Spinning up the motors, changing the controller inputs to vary the speed and direction Flipping the +/- wiring to observe direction change of the motor spin Measuring the voltage/amperage at different points in the setup Using an oscilloscope to visualize the signals Possibility an activity corresponding to lift and	3 hrs.
Troubleshoot and repair challenge	Failures are introduced in the quadcopters in one or more ways and students are required to troubleshoot and repair the quadcopter to its original functionality. Potential failures include: Break a motor (replace a motor with a broken one) Reverse wiring Damaged control board Break a propeller	3 hrs.

Table A3. Agenda for Workshops 2, 3-D Printer Module

Module Name	**Module Description**	**Duration**
Overview	Demonstration of 3D Printer, overview of the website, Introduction to the pedagogical approach	1 hr.
Introduction to 3D Printer Kit	Online course on about 3D printer components and step- by-step instructions on how to assemble it. Objective is to develop some basic know-how with assembling circuits and mechanical parts, and build confidence in working with these systems.	3 hrs.
Hands-on exercises	Online Lectures with small kit experiments interspersed to give a break from watching the videos and to provide demonstrations of concepts. Topics include: 3D printer operations methods Extruder Height	3 hrs.
Troubleshoot and repair challenge	Failures are introduced in the 3D printer in one or more ways and students are required to troubleshoot and repair it to its original functionality. Potential failures include: Motor failure (replace a motor with a broken one) Reverse wiring Damaged control board Incorrect extruder height resulting in poor print quality Requirement of larger build area requiring	6 hrs.

Appendix B

Table B1: Pre and Post multiple-choice answers (correct answers show change)

Q1. How is resistance measured?	**Post**	**Pre**	
Amperes	10%	8%	
Newton	0%	8%	
Ohms	90%	67%	↑
Guess	0%	17%	
Q2. How is Current Measured?	**Post**	**Pre**	
Amperes	90%	75%	↑
Volts	10%	17%	
Guess	0%	8%	
Q3. If you increase the voltage of the battery in a circuit, how will the current change?	**Post**	**Pre**	
Cannot be determined	10%	17%	
Decreases	10%	8%	
Increases	60%	42%	↑
Stays the same	20%	8%	
Guess	0%	25%	
Q4. If you connect two batteries in a parallel, what happens to the voltage in the circuit?	**Post**	**Pre**	
Doubles	50%	17%	
It's not safe to connect batteries in a parallel	0%	8%	
Stays the same	40%	50%	↓
Guess	10%	25%	
Q5. If two resistors are connected in series, how is the total resistance calculated?	**Post**	**Pre**	
Add the reciprocals of each and then take the inverse of the result	20%	0%	
Multiply the reciprocal of each value and then take the inverse to obtain the result	0%	17%	
Multiply the reciprocals of each value and then take the inverse of the result	20%	0%	
The two resistance values add	40%	0%	↑
The two values add	0%	25%	
The two values multiply	0%	17%	
Guess	20%	42%	
Q6. The multimeter is set at 20 DCV setting. The reading is 0.40. What is the voltage across the component?	**Post**	**Pre**	
0.40V	20%	42%	↓
4.0V	30%	17%	
8.0V	10%	8%	
Guess	40%	33%	

Table B2: Pre and Post multiple-choice answers (continued ...)

Q7. How do electromagnets work?	**Post**	**Pre**	
Current generates a magnetic field.	40%	25%	↑
Electric field generates a magnetic field.	30%	42%	
Moving magnets generate current in the wire.	20%	0%	
Guess	10%	33%	
Q8. How is a brushless motor sped up?	**Post**	**Pre**	
Increase the electric current.	40%	0%	
Increase the frequency of current switching.	30%	33%	↓
Increase the voltage current	0%	25%	
Increase the voltage.	20%	8%	
Reduce gear	0%	8%	
Guess	10%	25%	
Q9. When you rotate an electric motor using your hand, you will notice that it won't stay at certain angles; it'll always go into a few resting positions. Why?	**Post**	**Pre**	
The electromagnets have residual magnetic field and resist movement when off.	0%	17%	
The grooves in the shaft interfere with electric circuitry	0%	8%	
The permanent magnets attract the metal parts and don't align in all angles.	50%	50%	↔
The electromagnets have residual magnetic field and resist movement when off.	40%	0%	
Guess	10%	25%	
Q10. An oscilloscope is capable of measuring which type of electrical signal?	**Post**	**Pre**	
Capacitance	10%	8%	
Current	30%	33%	
Resistance	10%	0%	
Voltage	20%	17%	↑
Guess	30%	42%	
Q11. You see a waveform repeating twice on an oscilloscope screen that has 10 divisions and is set to 1 millisecond per division. What is the frequency of the signal?	**Post**	**Pre**	
10 Hz	50%	42%	
200 Hz	10%	17%	↓
5 Hz	10%	8%	
Guess	30%	33%	

Table B3: Pre and Post multiple-choice answers (continued ...)

Q12. A signal is currently taking up five vertical divisions. You switch the VOLTS/DIV dial from 1V to 2V. How many vertical divisions is the signal taking up now?	Post	Pre	
2	10%	17%	
2.5	10%	17%	↓
10	40%	0%	
Guess	40%	67%	
Q13. Before connecting a signal source to the oscilloscope, it is important to verify which of the following?	**Post**	**Pre**	
All of the above	70%	58%	↑
The signal source does not exceed the oscilloscope current limit	0%	8%	
The signal source is grounded to the same ground as the oscilloscope	0%	8%	
Guess	30%	25%	
Q14. What is the period of a wave?	**Post**	**Pre**	
The acceleration of the wave	0%	8%	
The height of the wave	10%	8%	
The shape of the wave	10%	0%	
The time (or distance) between wave peaks	60%	58%	↑
Guess	20%	25%	
Q15. What shape of wave is typically used for pulse width modulation?	**Post**	**Pre**	
A circular wave	10%	0%	
A sine wave	40%	25%	
A square wave	30%	17%	↑
A triangular wave	0%	8%	
Guess	20%	50%	
Q16. How does frequency relate to period?	**Post**	**Pre**	
frequency = 1 / 2 x period	0%	8%	
Frequency = 1/period	60%	42%	↑
Frequency = period	10%	0%	
Guess	30%	50%	
Q17. What is the amplitude of a wave?	**Post**	**Pre**	
The height of the wave	70%	67%	↑
The shape of the wave	10%	0%	
The time (or distance) between wave peaks	0%	8%	
Guess	20%	25%	

Table B4:Pre and Post multiple-choice answers (continued..)

Q18. What is pulse width?	Post	Pre	
The length of time in the wave cycle in which there is no voltage being applied	0%	8%	
The length of time in the wave cycle in which there is no voltage being applied	30%	0%	
The length of time in the wave cycle in which there is voltage being applied	50%	17%	↑
The period	0%	8%	
The voltage applied	0%	17%	
Guess	20%	50%	
Q19. How does a quadcopter increase altitude?	**Post**	**Pre**	
By increasing the rotor diameter	30%	17%	
By increasing the ESC input voltage	0%	42%	
By increasing the speed of all motors equally	60%	0%	↑
Guess	10%	42%	
Q21. What would happen to a standard quadrotor when one of the clockwise spinning motors suddenly stops working?	**Post**	**Pre**	
Steadily spin clockwise	10%	8%	
Steadily spin counter-clockwise	10%	8%	
Wobble about pitch, roll and yaw axis, and descend	60%	58%	↑
Guess	20%	25%	
Q23. What frequency range do radio controlled airplanes communicate on?	**Post**	**Pre**	
SHF: Super High Frequency (3 to 30 GHz)	20%	8%	
UHF: Ultra High Frequency (300 to 3000 MHz)	30%	25%	↑
VHF: Very High Frequency (30 to 300 MHz)	10%	17%	
Guess	40%	50%	

Appendix C

Table C1. Ratings used to assess Pre/Post Concept Question Responses for Workshop 2

1 = Does not understand the concepts, no exposure to such concepts before
2 = Familiar with terminology for a particular system, but may not know the systematic approach
3 = Basic understanding of the systematic approach, however may not be able to translate to other systems
4 = Good understanding of the systematic approach, should be successfully able to translate to other systems of similar complexity
5 = Exceptional understanding, should be able to translate to other systems of advanced complexity

Table C2. Participants answers rated as per grading scheme shown in Table C1

	Did the participant demonstrate understanding of the Electromechanical System?		**Did the participant demonstrate understanding of the technical issue?**		**Did the participant provide acceptable approach in diagnosing the fault/issue?**		**Did the participant provide acceptable approach to repair the issue?**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Participant 1	4	4	4	5	4	4	4	4
Participant 2	2	4	3	4	3	4	4	4
Participant 3	5	5	4	5	4	5	5	5
Participant 4	4	4	5	5	5	5	5	5
Participant 5	3	4	3	3	3	5	1	5
Participant 6	5	5	5	5	5	5	3	5
Participant 7	1	4	1	4	1	3	1	5
Participant 8	3	5	4	4	4	4	3	4

Appendix D

Table D1: Facilitators' Observations Workshop 1

	How difficult were the mini-kit activities for the participants? What did they appear to struggle the most with?
1st iteration	Participants used the mini-kit to test out parts before installing them on the quadcopter
2nd iteration	Wasn't very clear to them as to how to use the mini-kit
3rd iteration	Wiring seemed to be the most difficult part of the mini-kit. One participant wired the ESC incorrectly which caused a problem with the battery.
	How did the participants use the website? Which content did they favor or engage with?
1st iteration	Participant used the video highlights for navigation of the site to find the videos he needed to watch to get the info he wanted
2nd iteration	Participants liked the website format and content. However, they had to search through a lot of videos for some specific instruction that was not easy to locate.
3rd iteration	The quad rotor assembly and wiring videos were used primarily. Supporting lecture videos were used to a lesser extent when participant found that information in the quad rotor assembly and wiring videos was insufficient. Participants seemed to make use of the supporting text when watching lecture content (not assembly or wiring videos).
	How much intervention was required from you in order for the students to be successful? Do you feel that this intervention was in areas relating to what was taught in the course or in additional skills that were not covered here?
1st iteration	Participant asked permission to break the course order and start building (opposite of approach from non-military students). Not much intervention was requested, except for operating the quadcopter.
2nd iteration	Requested help with connecting the receiver.
3rd iteration	This group did not finish the task, and so little assistance was provide on our end. The only assistance given was when the participant wired the ESC wrong. We corrected the situation to avoid an unsafe situation with the battery. Participants gave up between halfway through assembly and the final assembly of the quad copter. None participated in the troubleshoot task.
	With respect to the troubleshooting exercise: How long did it take? How much did they struggle?
1st iteration	When spare parts are available, participants jump right to swapping out broken parts rather than try to diagnose the problem with the part
2nd iteration	Participants fixed all the problems by replacing parts that they diagnosed were causing a problem. Some identified wiring problems and fixed them by soldering them.
3rd iteration	Participants in this group gave up on the activity before the troubleshooting task, and so no evaluation was made here.

Table D2: Facilitators' Observations (Continued …)

	With respect to the challenge problem: How long did it take? How much did they struggle?
1st iteration	This task was not conducted in the workshop.
2nd iteration	This task was not conducted in the workshop.
3rd iteration	This task was not conducted in the workshop.
	How did the student's original challenge plan compare to their final implementation? Were they able to correctly identify and resolve any issues with the original plan? Can you describe the process you observed them using to solve the challenge?
1st iteration	This task was not conducted in the workshop.
2nd iteration	This task was not conducted in the workshop.
3rd iteration	This task was not conducted in the workshop.
	Any other observations or comments you would like to document and share?
1st iteration	Not all participants have a high school level of computer skills. Some participants preferred to test parts during assembly not operation
2nd iteration	Participants seem to be divided into those that would start working with the hardware while watching the videos, and those that preferred to first watch the videos and then work with the hardware. The second group were not as effective at completing the task.
3rd iteration	This group seemed to lose interest in the task. One participant completed the assembly and did not do the troubleshooting task. Other participants did not complete the assembly task.

Table D3: Workshop 2 Facilitators' observations

Q1	**With respect to the challenge problem: How long did it take? Did they struggle?**
	Only one group performed the extra exercise. They made a pan/tilt attachment to mount a flashlight. They had no trouble and completed it in approximately 1.5 hours.
Q2	**How did the student's original challenge plan compare to their final implementation? Were they able to correctly identify and resolve any issues with the original plan?**
	The original and final plan were identical and remained unchanged throughout. They implemented the design and it worked on the first try. The general steps they took were: - Identify the needed function - Figure out which parts they had access to - Form an idea for the general layout of the mechanism - Design the custom parts they would need - Manufacture and assemble
Q3	**Any other observations or comments you would like to document and share?**
	The participants were in general already familiar with a lot of the website content and fundamentals. Some of the participants did not watch all the videos and instead relied on static content to assemble the kits.