MECHATRONICS FOR HUMANITARIAN

Over the past six years, researchers at Villanova University (VU) and the Golden West Humanitarian Foundation (GWHF) have developed an integrated research and educational program focused on the use of mechatronics and robotics in humanitarian explosive ordnance disposal (EOD) and mine action. In the following article, I will talk about this program, discuss two ongoing projects – a low-cost EOD robot and an automated ordnance identification system – and talk about how we have successfully integrated students in the work. There are many opportunities for the DSCD community to get involved in this area and hopefully this article will pique your interest.

DO YOU WANT TO GO TO CAMBODIA?

During the last week of spring classes in 2012, I was standing at the Villanova Mechanical Engineering copier, making copies of the final exam for my Mechatronics class. Jordan Ermilio, director of the Villanova Engineering Service Learning (VESL) program came out of his office and said, "Garrett, do you want to go to Cambodia?" I enthusiastically said, "Yes!" This caught him by surprise and asked if I should check with my family first. This was a good point, so I did. They were in support of the trip, and 3 weeks later I was on my way to Phnom Penh with Jordan and a group of 3 students to lay the groundwork for a very non-mechatronic construction project. As luck would have it, on the flight from Taipei to Phnom Penh, one of the students traveling with us sat next to Len Austin, GWHF's EOD Special Operations Chief. He invited us to visit GWHF's testing facility, we accepted, and over dinner with Len and Allen Tan, Director of Technology at GWHF, we decided to collaborate on a low-cost EOD robot (discussed in more detail below). Six years later, I have spent more than 6 months in Cambodia working on a broad range of projects focused on developing mechatronic and robotic solutions to issues in humanitarian mine action and EOD. For some context about why this work is done in Cambodia, see **Sidebar 1**: "Cambodia's Recent History."

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EXPLOSIVE ORDNANCE DISPOSAL IN CAMBODIA

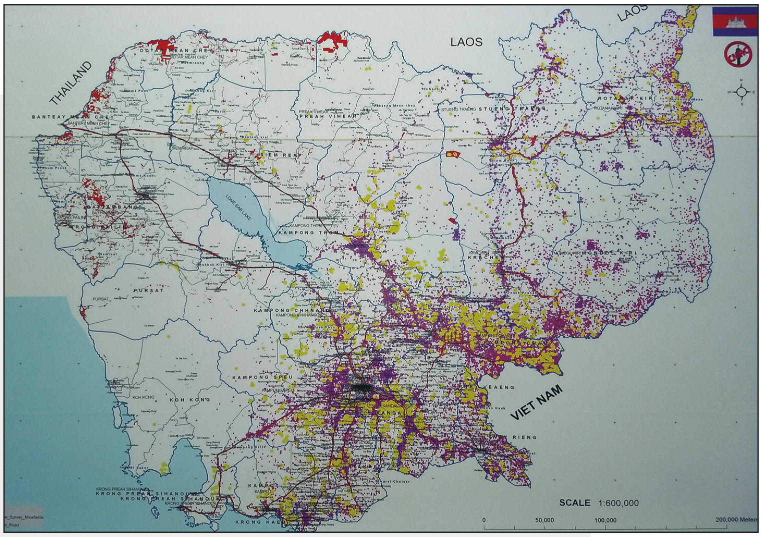

FIGURE S1 **Map showing unexploded ordnance (UXO) in Cambodia from the Cambodian Mine Action Centre's "Peace Museum for Mine Action" in Siem Reap, Cambodia. Legend: Yellow/Purple - US Bombing Sites, Red - Minefields.**

S1: CAMBODIA'S RECENT HISTORY

Starting in 1965 and continuing for three decades, Cambodia was embroiled in armed conflict. US bombings during the Vietnam War made Cambodia one of the most bombed countries in history [1]. Many bombs did not explode, leaving un-exploded, but still active bombs throughout the country (US bombing sites are shown in yellow/purple in **Figure S1** along the Cambodia-Vietnam border.) Following this period, the Khmer Rouge came to power, resulting in the Cambodian genocide [2]. The Khmer Rouge were eventually pushed to the Cambodia-Thailand border, where landmines were deployed by Vietnam, Cambodia, and Thailand to prevent the Khmer Rouge from entering their respective countries [2] (active landmine sites are shown in red in **Figure S1** along the Cambodia-Thailand border).

In Cambodia, more than 1970 km^2 of land is contaminated by explosive remnants of war (ERW) [2]. During the period 1979 to 2017, there have been 64,688 recorded casualties associated with mine/ERW [2-4]. Economic growth is stifled because expansion of farms and other livelihood activities have been impeded [2]. Thus, there is a critical need to remove these threats. More broadly speaking, it is estimated that 100 million landmines are spread throughout 84 countries and that landmines kill or injure 20,000 people each year, worldwide [5]. This problem is compounded by the fact that many of these ERW are in low-income countries that cannot afford technologies that make removal easier and faster [5, 6].


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FIGURE S2 **GWHF lead engineer, John Wright, holding one of GWHF's 3D printed EOD training aids.**

S2: THE GOLDEN WEST HUMANITARIAN FOUNDATION

One noted difficulty with working in humanitarian robotics is access to expertise [7]. Our work does not suffer from lack of access to expertise because of our strong and continuing collaboration with the Golden West Humanitarian Foundation (GWHF), a US-based NGO recognized by the international humanitarian mine-action community as one of the premier non-governmental organizations for the research, development, and implementation of solutions to address this sector's most difficult technical challenges. GWHF brings EOD expertise, highlighted by an interdisciplinary staff of experts considered to be one of the best in the fields of EOD, detection technologies, and engineering research and development. In addition, GWHF has a long history of product development exemplified by their extremely successful 3D printed EOD training aids, shown in **Figure S2**.

MECHATRONICS IN HUMANITARIAN EOD AND MINE ACTION

Before we begin discussing mechatronics in humanitarian EOD and mine action, it is important to make the distinction between military and humanitarian missions. The goal of military EOD is to render a threat safe and/or create safe routes for soldiers. This requires, for example, only partial clearance of mine fields. In contrast, humanitarian operations focus on completely removing threats in order for the land to be used safely – in the minefield example above, 100% clearance is desired. One could argue that the latter is the more difficult task, which underscores the need for advanced engineering fields, like mechatronics, to be applied in humanitarian EOD and mine action.

Why haven't the benefits of mechatronics been realized in humanitarian EOD?

Partially the answer to the question above is about perception. When one thinks of "humanitarian engineering," thoughts of "low-tech" or "old-tech" might come to mind. These thoughts are in direct conflict with mechatronics, a high-tech, cutting-edge field. This dissidence between humanitarian engineering and mechatronics might leave any engineer worrying that robustness and/or safety have been traded for affordability. This trade-off between robustness/safety and affordability, however, is diminishing as the cost and availability of components necessary for mechatronic devices become cheaper and more widely available. Consider that relatively high-power computer boards (e.g., Raspberry Pi) and relatively easy-to-program microcontroller boards (e.g., Arduino) are both available for under $10. These components are even in-stock at stores in low-income countries provided you know where to look, making developments in mechatronics relevant and important in low-income countries.

Mechatronics in EOD

More generally speaking, mechatronic systems are used quite broadly in EOD, especially in higher-income countries. Systems that can detect, identify, handle, move, disarm, destroy, manipulate, or, in general, observe and/or interact with ordnance while keeping human operators safe are of the utmost interest to the EOD community. Currently, there are two key areas within mechatronics that have made significant impacts in this community – robotics and sensing.

Robots are widely used in EOD, allowing operators to interact with ordnance without direct contact [8,9]. There has also been a great deal of work on landmine robots [10,11]. Although these are not currently deployed in Cambodia there are a number of new

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FIGURE 1 **The VU-GWHF EOD robot performing a simulated EOD mission. Photo taken at the GWHF test facility in Kampong Chhnang, Cambodia.**

initiatives and companies aimed at developing robots for mine action in Southeast Asia.

Ordnance sensing (e.g., detection) is also an active mechatronics-related research field which has had an impact in humanitarian demining. Research in this area is focused on signal processing and statistical methods, as well as sensor design and development [12]. Novel instruments are constantly being developed like the new Scorpion unexploded ordnance (UXO) detector developed by the US DoD through the Humanitarian Demining Research & Development (HDR&D) program.

VU-GWHF RESEARCH PROGRAM

Along with our project partner GWHF (see **Sidebar 2**: "The Golden West Humanitarian Foundation" for more information), we have been working on a broad range of problems in humanitarian EOD and mine action. Everything from the mechatronics-related projects I will discuss in more detail below, to life-cycle analysis studies on GWHF's Explosive Harvesting program to field-deployable fume hoods to lessen the environmental impact of ordnance disposal. In this section, I am going to discuss, in brief, two ongoing projects.

The VU-GWHF Low-Cost Explosive Ordnance Disposal Robot

After that first chance meeting, the VU-GWHF team began work on a low-cost EOD robot. Robots are widely used in EOD, allowing operators to interact with ordnance, e.g., an improvised explosive device (IED), without direct human contact. Typical EOD robots have a robotic manipulator with varying degrees of freedom (multi-link arms with versatile grippers), a number of cameras, are able to traverse diverse terrain, and are remotely-operated. Many different robots have been developed, for example military-grade robots like the Talon [9] or the PacBot [8]. Even though there has been a large amount of work in EOD robotics, the current commercially-available robots are too expensive for use in low-income countries. Note that even when initial purchase prices can be lowered, the maintenance costs can be significant, presenting an additional barrier.

The VU-GWHF low-cost EOD robot [13] can be seen in **Figure 1**. Although I could discuss the many technical challenges we encountered while developing this robot, perhaps the most interesting difficulties we encountered were centered on designing for use and/or manufacture in low-income countries. When we first approached this problem, we put cost as our most important design constraint, which led to a robot constructed out of PVC and parts that could be entirely sourced in Cambodia. While this makes sense because cost and supply chain are major concerns, at our first design review, GWHF made it clear that PVC wouldn't cut it. Reliability/robustness and functionality were, in some cases, more important than cost and we could justify spending more on and importing critical parts and materials (although cost could never be forgotten).

Once the interplay between these three main design considerations (cost, reliability, and functionality) was established, we set out to produce an EOD robot that had 90 percent of the functionality of military-grade robots at 10 percent the cost. This led to tradeoffs in a number of the robot's subsystems, which leaves it different from typical military EOD robots in a number of ways as discussed below.

1. Robotic Manipulator: The robot has a relatively-simple 2DOF arm, which stands in stark contrast to commercial robot arms, which can be highly articulated [8]. This choice was made to reduce cost and increase robustness and field repairability. In consultation with GWHF EOD specialists, it was decided that this arm would still be useful in many EOD missions. Note that the linear actuators that drive the arm are high-end actuators that can withstand the harsh environments in which the robot will be deployed – an example of when high-cost components can be justified.

2. Drive System: The robot's drive system uses wheels, not tracks. Wheels were chosen to reduce cost and maintenance but limit the robot's ability to handle difficult terrain. This design decision was perhaps the most difficult to make because treads would vastly expand the robot's capabilities. In this case, cost and reliability outweighed functionality.

3. Electronics and Communications: The robot's control electronics are almost entirely chosen from maker-movement technologies, i.e., Arduino, Raspberry Pi and lower-cost components. Note that these low-cost computational components do not allow the flexibility in programming of higher-cost, higher-power targets, resulting in a trade-off between functionality and cost. Wireless communication was identified as a critical subsystem, so higher-cost components (resulting in higher functionality and reliability) were justified.

Current Status: Current efforts on this project are focused on developing a production prototype. We are hoping to have these robots available for field work in the next year.

FIGURE 2 Example images of mortars showing, from left to right. Top row: Yugoslavian M47 HE, Chinese Type 22, Chinese Type 30, USSR S832SM Illumination. Bottom row: Vietnamese Propagande Model UNK, USA M374 series HE, USSR F-843

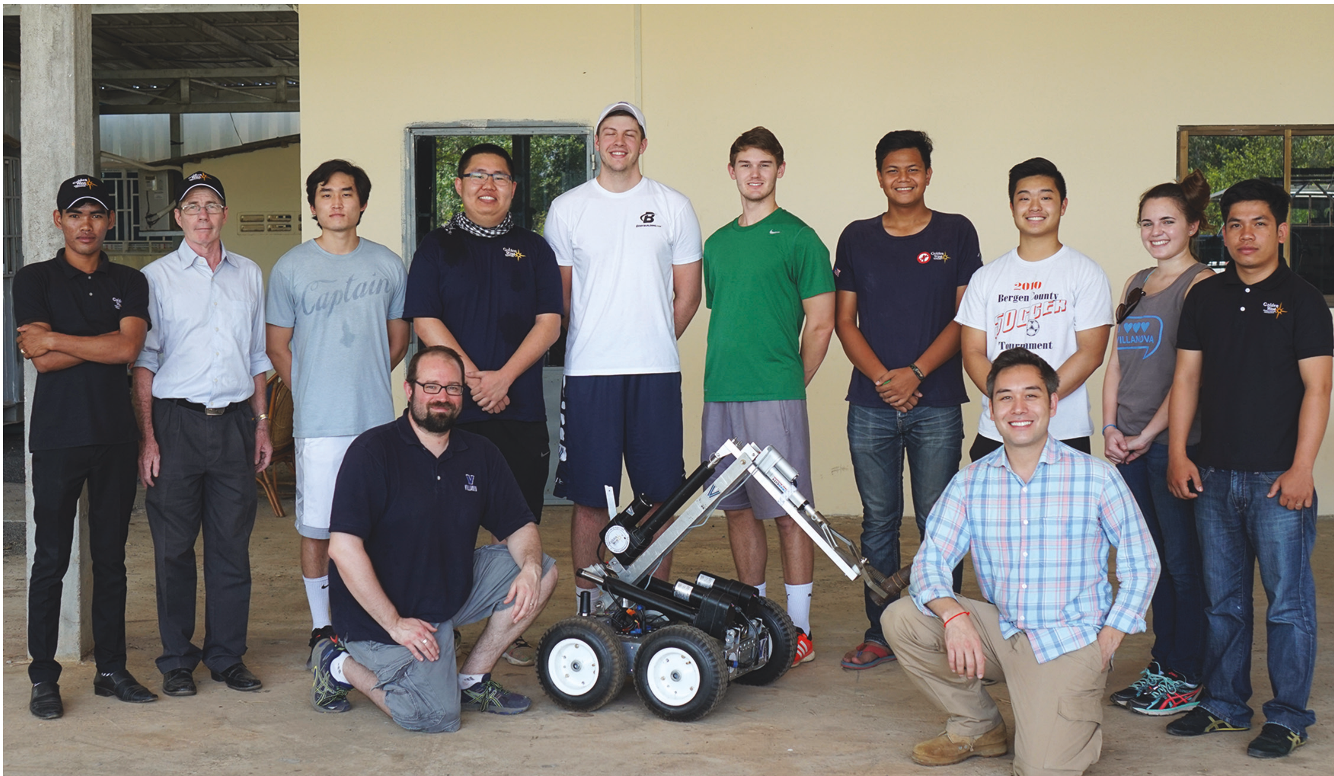

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FIGURE 3 **The 2015 EOD robot team during field work in Cambodia at GWHF's Kampong Chhnang testing facility.** ***From left to right.*** **Back row: Chenda Nget (GWHF Engineer), John Wright (GWHF Lead Engineer), John Lim, Denzen Boldsikhan, Anthony Marone, Ian Stankosh, Sombo Heng (GWHF Programmer), Christopher Hsu, Samantha Tropeano, Dim Samach (GWHF Engineer). Front row: Garrett Clayton, the EOD robot, Allen Tan (Director of GWHF's Design Lab).**

Automated Ordnance Classification Support System

A more recent project, which is co-led by Dr. C. "Nat" Nataraj at VU, focuses on the development of an automated ordnance classification system to aid EOD technicians [14]. In typical EOD missions, classification of the ordnance that is being dealt with is of critical importance as it dictates how the EOD technician will approach the situation. High-confidence classification requires an expert with a great deal of training and experience. This expertise is not always available in low-income countries, so this project seeks to aid EOD technicians in low-income countries in the ordnance classification process through the use of machine learning.

The concept for this classification support system is that an EOD technician will take a picture of a piece of ordnance and the system will return potential ordnance matches using a ConvNet classifier [14]. While these techniques are well established in machine learning, the availability of ordnance image datasets is limited or non-existent. Thus, the first step in this project was to acquire such a dataset. This dataset is composed of images taken from ordnance libraries belonging to GWHF, the Cambodia Mine Action Centre (CMAC), and other libraries in Europe.

ABOUT THE AUTHOR

Garrett M. Clayton is an Associate Professor in the Department of Mechanical Engineering and the director of the Center for Nonlinear Dynamics and Control at Villanova University. His current research interests are broadly spread throughout the area of mechatronics with specific applications in nanopositioning, remote monitoring, humanitarian technologies, and robotics. Dr. Clayton received his Bachelor of Science in Mechanical Engineering from Seattle University in 2001 and his Masters of Science and PhD in Mechanical Engineering from the University of Washington in 2003 and 2008, respectively. His research has been funded by the National Science Foundation (NSF), the US Environmental Protection Agency (USEPA), the Pennsylvania Department of Transportation (PennDOT), and the Golden West Humanitarian Foundation (GWHF) and a number of small companies. He recently received a Fulbright Research/Teaching grant to live and work in Cambodia in the summer of 2018.

Our growing image database currently has more than 250 different types of ordnance. Example images of mortars can be seen in **Figure 2**.

Preliminary results have been promising. As reported in Ref. [14], classification of mortars from the set in **Figure 2** was found to be 97% accurate. Current work is focused on expanding the image database, testing the methods on additional types of ordnance, and enabling the classification of partially-occluded ordnance and ordnance in field conditions.

STUDENT INVOLVEMENT

During the course of this project, more than 60 students have taken part in these collaborative projects through senior design projects, summer internships and fellowships, undergraduate research, Master's theses, PhD dissertations, and volunteer work. Of these 60 students, more than 20 have traveled to Cambodia for field work (some for trips as long as two months). A few of these students are shown in **Figure 3** with some of our collaborators at GWHF. Anecdotally, these international project experiences have affected the students in a meaningful way: more than 10 have entered the armed forces (3 in the Navy nuclear program's highest engineering position and at least one in EOD) and more than 15 have gone on to pursue advanced degrees in engineering. We will continue to involve a broad range of students through a recent NSF International Research Experience for Students (IRES) grant to expand summer fellowships.

CONCLUSION

The VU-GWHF research program discussed above is focused on the use of mechatronics and robotics to solve problems in humanitarian EOD and mine action. Two ongoing projects were presented that seek to address needs specific to low-income countries like Cambodia. As stated previously, there are a number of intriguing, difficult, rewarding problems to which the DSCD community could contribute solutions. If you are interested in these problems, I encourage you to reach out to me for more information. Collaborators are welcome! ■

ACKNOWLEDGEMENTS

This work could not have been possible without the many students who have taken part. I thank them all, but would like to specifically thank Michael Benson and Anderson Lebbad who have spent nearly as much time in Cambodia as I have. I would also like to thank my colleagues, Dr. C. "Nat" Nataraj (VU), Dr. Jordan Ermilio (VU), Allen Tan (GWHF), and John Wright (GWHF), all of whom I have collaborated with very closely on these projects. Finally, I would like to thank our sponsors for their generous support. The initial trip to Cambodia was funded by the Caramanico Foundation (they continue to support projects in Cambodia to this day). GWHF, through a U.S. State Department Grant, has supported a number of senior design projects, summer internships, and graduate theses and dissertations. Current work is funded through a Fulbright Scholar grant and an NSF IRES Award (Award Number 1658696).

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