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**EDITORIAL**

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We are at the edge of a Cambrian explosion in robotics and autonomous systems. Capabilities being demonstrated by government-sponsored research organizations and backyard hobbyists alike are incredibly impressive, from biomimetic robotic birds to Unmanned Aerial Vehicles (UAVs) built from LEGO® bricks. Progress in this new era will be fast moving, commercially driven, and a result of unprecedented integration — to the point of blurring the distinction between hardware and software.

Despite our collective fascination with robotics and autonomous devices both real and fictional, they will for the foreseeable future remain deterministic machines, governed not by Asimov’s laws but by a combination of economics and programming. Robotics and autonomous systems will be embraced whenever the risk-adjusted return on investment for developing and deploying them is compelling. The philosophical question, “Will humans be in the loop?” can be answered definitively: “Yes, humans will always be in the loop,” with the tacit acknowledgement that “in the loop” means responsible for the programming, algorithms, and decision-making implementation of robotics and autonomous systems. It does not mean that a human will be informed of, let alone be able to respond to or override, the outcomes that occur in the milliseconds between data collection and direct action. This suggests the possibility that we may be entering a post-informational age, where the ability to program and automate behaviors in response to information surpasses in value the mere possession of information. Human programmers ultimately will

Law #1: A robot may not injure a human being, or through inaction, allow a human being to come to harm.

Law #2: A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.

Law #3: A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

— Isaac Asimov, Laws of Robotics from *I, Robot*, 1950
be the ones responsible for upholding or breaking Asimov's laws and, to Caesar's point, to what end?

The recent growth of robotics in combat theaters has been well described and is representative of the potency of the combination of economics and programming. Beyond the battlefield, there are significant Intelligence Community applications and implications inherent in the anticipated expansion of robotics and autonomous systems. IQT is well-positioned to play a pivotal role in shaping the development of robotic and autonomous systems for the Intelligence Community's specific needs and anticipating the implications of the technology as it unfolds in real time. With deep expertise in physical, biological, information, and communication technologies, IQT has first-hand experience investing in robotic and autonomous systems, which directly informs a strategy for addressing both the pragmatic and strategic issues surrounding development in this area.

For the purposes of IQT's strategic approach, robots and autonomous systems can be described by their ability to exhibit "agency," the capacity to act in the world. This includes physical agency (i.e. the ability to move or manipulate physical objects) coupled with intellectual agency (i.e. a control system that responds to inputs and stimuli from its environment and takes independent responsive action). By this definition, the famous clock of London, Big Ben, would not be considered robotic or autonomous despite its legendary reliability and complex chime sequence. However, the alarm clock that actively evades you by rolling away when you try to hit the snooze button would fit the criteria. The concepts of physical and intellectual agency fit nicely with the reductionist viewpoint that everything can be classified as hardware or software; "atoms" or "bits" so to speak.

With robotics and autonomous systems defined by their ability to exhibit physical and intellectual agency, the technical challenges and opportunities in the field can be further classified into four highly overlapping categories: power, processing, platforms, and payloads (Figure 1).

**Power and Processing**

Power management and processing capability are the foundations of robotic and autonomous systems. Ultimately, the power budget defines the mechanical agency and determines the limits of performance for duration, distance, speed, size, weight, payload capacity, etc. Equivalently, the processor capability governs the intellectual agency. The size, power consumption, and capability of one or more microprocessors go hand-in-hand with the power budget. Recent advances in robotic and autonomous systems are the direct result of power densities and energy harvesting capabilities increasingly coupled with improvements in the computational efficiencies of microprocessors and other microelectronics. Pushing the frontiers of power storage, management, and energy harvesting on all scales will remain an open challenge, but will require concrete gains over existing solutions to gain acceptance.

**Platforms**

The available energy dictates the form factor and mission space for a physical platform, which is the backbone of a robotic or autonomous system. This is how physical agency is manifested, through propellers, wheels, legs, arms, and a myriad of other components. Platform technology has benefited tremendously from advances in lightweight structural materials and improvements in multiphysics, computer-aided design, and simulation. Beyond the design stages, software/firmware development of algorithms to control, calibrate, and compensate are critical to the integration of the mechanical components. There remains substantial open space in
the area of novel platforms. In addition to the various creative permutations on tracks and wings, biomimetic platforms continue to make impressive strides (see, for example, Dr. Hylton’s article in this issue, and should continue to provide a wellspring of innovation and hybridization concepts.

**Payloads**

Payloads, as defined here, include both internal and external devices. For example, GPS receivers, laser range finders, acoustic sonars, stereo optical cameras, and communications packages that can be used for geospatial location and navigation can be considered internal payloads as they are integral for the system’s autonomy. However, more task-oriented devices such as water samplers, radiation detectors, or electro-optic video feeds to a remote operator can be considered more traditional payloads or external devices. Core internal devices will continue to shrink at an impressive pace in size, weight, and power consumption, and increase in capability to the point that they are expected to become commoditized. This is good news for systems builders and consumers, but challenging for domestic component producers. This suggests these devices will migrate to offshore contract manufacturers. Opportunities will be available for higher level, mission-specific functional devices of reduced size, weight, and power consumption and for incorporating more computing at the edge.

Implicit in the development of robotic systems and autonomous devices is the desired characteristic of dependability. Dependability includes measures and expectations of reliability, integrity, interoperability, security, uptime, safety, ruggedness, etc. While dependability is critical for acceptance and highly non-trivial to achieve and demonstrate, it is often considered late in the development stage. As the field continues to mature, dependability of all components — hardware, firmware, and software — will need to be “designed in” as early as possible and not as an afterthought to be upgraded in the field.

These are thrilling times to be a technologist. It is not a question of if robotics and autonomous systems will become pervasive, persistent, and ubiquitous, but simply a matter of when and what the details will look like. It will assuredly also contain some surprises. We are at a point where more and more of our futuristic concepts are becoming manifest in universities, laboratories, garages, and companies worldwide. Most of these scientists, engineers, and hobbyists share an optimism that developing robotic and autonomous systems technology will result in a net positive towards the goals of peace and prosperity. In the end, robots are closer than you think, but not what you imagined. They are tools, extensions of who we are, but deterministic nonetheless, governed by economics and algorithms. They will continue to evolve with increasing complexity, and like all tools, will create both new opportunities and new threats.

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**Dr. Frank DiMeco Jr.** has been at IQT since mid-2007, and holds the position of Technology Vice President within the Physical and Biological Technologies Practice. He manages the Extending the Reach theme within the practice, which encompasses autonomous platforms, payloads, and power. Prior to joining IQT, his research spanned several technology areas including: semiconductor research, MEMS gas sensors, nanotechnology, and related product development in both government and commercial establishments. His 21-year career has included 17 patents and R&D 100 recognition. DiMeco holds a Bachelor of Science and Engineering (with dual majors in materials science and electrical engineering) from the University of Pennsylvania, and a Ph.D. in Materials Science and Engineering from Northwestern University.

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1. “Seven Questions for the Age of Robots,” Jordan B. Pollack, Yale Bioethics Seminar, Jan 2004
2. The Intelligethics Age, a contraction of Intelligence and Ethics (principles that govern behavior), seems to fit as a possible moniker for this particular vision of the Post Informational Age.
3. See for example, Wired for War, by P.W. Singer, 2009
4. The recently announced National Robotics Initiative is another example of going beyond the battlefield. It is telling that this program as unveiled by President Obama, was deemed critical for national economic defense, as key to growing our domestic manufacturing base, not for traditional Department of Defense applications, per se.
A LOOK INSIDE — HUMANS IN THE LOOP

By Frank DiMeo Jr.

The Summer 2011 issue of the IQT Quarterly highlights some of the most exciting recent developments of robotic and autonomous devices while considering the evolution of human interaction with these systems and their potential use in both commercial and military applications.

Whether in a government, commercial, or garage setting, trying to do more with less is a constant driver, and robotic and autonomous systems are ideally suited to provide this desired leverage and extension of reach. Realization of both of these capabilities is driving development on all fronts (air, land, and sea) and across multiple communities (academic, commercial, military, intelligence, first responder, and hobbyist). This IQT Quarterly presents a small, but diverse, cross section of these developments, yet offers representative motivations and examples of leverage and extension of reach in action.

A terrific example of robot enthusiasts trying to do more with less are the passionate hobbyists who prepare for events like RoboGames every year. Equally motivated to do more with less are the developers, both commercial and governmental, who are trying to have greater numbers of robots and autonomous systems placed under the control of a smaller number of operators, either in the warehouse or in the field. Systems are getting smaller, more intelligent, and more agile, allowing better access to even more challenging environments.

Developments in leverage and extension of reach converge in the field for rescue robotics and the operators who need to prepare and deploy into unknown, one-of-a-kind scenarios. Sharing of experiences and cross fertilization between these diverse groups and environments is sure to fuel the acceleration of robotics and autonomous systems in the years to come.

As Simone Davalos points out in her article, “Cross pollination is key.” This issue reflects that statement and seeks to demonstrate how dialogues between different groups of people with overlapping interests in robotics and autonomous systems will lead to more ingenuity, innovation, and ultimately implementation.

In Hobby Robotics and the Machine Revolution: Robotic Development at RoboGames, Davalos introduces us to International RoboGames, the world’s largest open robot competition. “The Olympics of Robotics” provides a competitive environment where roboticists can test and refine their technologies and interact with other enthusiasts. The event has driven the evolution of and respect for a class of robot hobbyists, who continue to find personal success as well as efficient, economical, and robust solutions in a field that had previously been dominated by academics, scientific researchers, and government development.
Next we consider how robotics can improve efficiency, flexibility, and accuracy in a traditional business system: warehousing in the global supply chain. In *Revolutionizing the Global Supply Chain*, Dave Munichiello of Kiva Systems discusses mobile robotic teams installed in distribution centers that continuously learn and are easily adaptable to different products and warehouse layouts. The technology allows businesses to respond to the rapid changes brought forth by eCommerce and an increasingly competitive market.

Drs. William J. Cohen and Ken Zemach of Exponent, Inc. contribute to this edition by discussing MARCbot, The Multi-function, Agile, Remote-Controlled Robot. MARCbot, Exponent’s answer to Improvised Explosive Devices (IEDs), is designed to inspect and identify suspected IEDs to maximize mission safety and efficiency for warfighters. Cohen and Zemach describe the in-theater applications of the technology, its design principles, and its life-saving benefit to American soldiers.

Warren Soloduk and John Klinger’s article, *The Future of Robotic Aircraft*, provides a strong bridge between robotics and autonomous systems used in the commercial sector and those employed in military operations. The use of Unmanned Aerial Vehicles has expanded impressively over the past 20 years. Initially developed by and for military and intelligence communities, smaller, more powerful UAVs are now operated for a variety of law enforcement and commercial functions. Expanded consumption and continuing improvement hint at likely trends in the development and function of UAVs.

*New Developments and Future Prospects for Small UAVs* is written by Dr. Todd Hylton, who managed the program at DARPA that developed the Nano Air Vehicle (NAV). The hand-sized UAVs, designed to look like hummingbirds, may prove to be an optimal tool for indoor and outdoor military operations in less accessible locations. Hylton also describes the extreme challenges of developing, powering, and communicating with such a minute machine without engineering or design precedents, as well as the many technical obstacles that still affect the deployment of the aircraft.

In an interview with Dr. Robin Murphy of Texas A&M University, we learn about Murphy’s work developing robots that can navigate earth, sky, and sea to perform rescue missions at disaster areas. She discusses her work since the first deployment of rescue robots on September 11, 2001 and what can be done to increase adoption of rescue robots in the U.S.

This issue’s *Tech Corner* features IQT portfolio company Semprius. To address the lack of access to a useable source of power in remote locations of the world, Semprius has designed a high efficiency, compact, lightweight, flexible solar fabric to generate portable energy. These concentrator photovoltaic (CPV) systems use the sun’s energy in remote locations to generate power for ground-based, mobile, and aerial electronics.

Beyond the technologies presented in this issue of the *IQT Quarterly*, robots and autonomous systems are being constantly developed and improved in garages, laboratories, and universities. Continued dialogues between hobbyists, startup entrepreneurs, academics, corporate research scientists, and government representatives will drive advancements in the field for years to come. This issue of the *IQT Quarterly* is intended to provide a cross section of these perspectives.
HOBBY ROBOTICS AND THE MACHINE REVOLUTION: Robotic Development at RoboGames

By Simone Davalos

Robotics used to be considered the sole purview of professional corporate research scientists or government contractors. While some advances in robotics over the years could only have come from a major university or organizations such as Honda Research Institute or Bell Labs, “garage” builders are now making comparable advancements in robot development, with the added advantage of being able to work unfettered by the constraints of a corporate or governmental environment.

Fueled by curiosity and spurred on by competition and community, hobbyists, tinkerers, home inventors, students, and other robotics enthusiasts worldwide create a vast pool of resources and knowledge in their garages, backyards, and after-hours labs. One of the nodal points for this web of innovation is The Robotics Society of America’s annual International RoboGames, the world’s largest open robot competition, which serves as a true test bed for technological shift.

RoboGames was founded by David Calkins, a robotics consultant, former robotics lecturer at San Francisco State University, and president of the Robotics Society of America, a 501(c)(3) educational nonprofit started in 1977. Conceived as “The Olympics of Robotics,” RoboGames welcomes competitors of every age, nationality, and skill level.

Enthusiasts, especially in engineering fields, tend to be single-minded. By making it easy for roboticists to see what one another are doing, RoboGames has become a developmental test bed and case study in robotic evolution. Cross pollination is key: The garage builders who exist in a vacuum in their garages or the university teams that never leave the ivory tower to explore what’s out there run a risk of reinventing the wheel. RoboGames provides affiliation both online and in the physical world, forming a supportive atmosphere for advancing development and an experimental community that provides a primordial soup of knowledge for the novice.

Offering more than fifty events, from bipedal humanoid competitions to autonomous navigation to heavyweight robot fighting, RoboGames was founded so that all roboticists can learn very effective and applicable lessons from one another, leading to technological hybrid vigor. Competition in robotics, as in a free-market economy, is the crucible that refines and hones the work each competitor presents, and provides an excellent proving ground for new technology. In other words, if the robot doesn’t work at the crucial moment in front of an expectant RoboGames crowd, it’s back to the drawing board. This also results in a much better robot the following year. Nothing inspires like failure.

The event, currently in its ninth year, has seen the evolution of the hobby roboticist from a primitive kit-bashing amateur to a force to be reckoned with by business and industry. For example, when Honda set the bar for bipedal motion with Asimo starting in 1986, solving what had been thought to be an unsolvable problem [semi]autonomous machine bipedal...
movement), it was the hobbyists in Japan who recognized the implications of Honda’s breakthrough. A few years after Asimo’s triumph, Japanese hobbyists were holding bipedal robotics competitions in Tokyo with home-built walking robots. In human athletics, this is the Roger Bannister Effect — several runners replicated Roger Bannister’s sub-four-minute mile run shortly after he broke down the barrier in 1954 (a feat previously presumed impossible). Once Honda had effectively solved the bipedal movement problem in the public sphere, other builders were inspired to work on their own bipedal projects, and were successful.

These competitors and their steadily evolving machines were introduced for the first time in the United States at RoboGames, and U.S.-based hobbyists were inspired to learn from the Japanese and run with the knowledge they gained. The conglomeration of U.S. and Japanese knowledge bases has resulted in bipedal autonomous and semi-autonomous androids that are increasing in size and power, built by people who have had to rely on creativity instead of budget. Single or small teams of builders spend thousands of dollars instead of millions, and the smaller teams develop areas that might not otherwise be economically feasible to cultivate, generating unexpected returns.

This sort of innovation would not be possible were it not for the existence of competitions like RoboGames, which provide not only inspiration and community, but also a deadline and a reason to build that is more easily taken advantage of by individual builders than by corporate R&D branches. The immediacy of the needs of the hobby roboticist makes it necessary for builders to find clever solutions to issues that arise when a builder does not have the budget of a government agency or the engineering resources of a massive company.

Tapping the informal robotics community is an economical and innovative approach to answering pressing questions in the field and encouraging the evolution of the technology as a whole. RoboGames contestants represent a wide variety of demographics and are not confined to professional engineers, companies, schools, or other formal organizations. This is an advantage. There is no way for one company or outlet to be proficient in every aspect of the field, therefore presenting the need for a solution to all is a sort of distributed computing engine that can solve seemingly insurmountable technological hurdles in years instead of decades.

Funding hobbyists and small companies has another advantage in that they are more willing to take enormous risks for the sake of their sport, and in a larger sense, for their area of robotics in general. In robot combat, one of the most popular events at RoboGames, a builder is willing to accept the possibility that his or her carefully hand-built, one-of-a-kind machine will get obliterated by the opponent, and that the builder will have to go back to the drawing board or increase their proficiency in any number of the myriad skills it takes to build such a machine. Often after their first attempt fails, combat builders will literally have to start fresh with a pile of parts. There is no tougher equipment proving ground for the amateur. This brutal environment leads to stronger, more reliable robots than what would come untested from a corporate lab.

The disadvantage to the hobbyist approach is the lower instance of funding opportunities. Hobbyists exist in a world of ingenuity and low overhead by necessity. There’s no spending cap on a robot, but there is a limit to the resources a hobbyist has at their disposal. Also, ingenuity is just as important as money, if not more so. At RoboGames, there have been instances of top of the line, CNC-milled solid titanium robots in the heavyweight division being trounced by $200 robots made of plywood and dry ice — resourcefulness and driving practice often make the difference in the arena.

The builders at RoboGames have also learned, seemingly counter-intuitively, that it is advantageous to be as helpful and supportive to their opponents outside the arena as they are ruthless and competitive inside. The builders, no matter what their competition, want to
face opponents who are in top condition in order to know that they themselves did the best they could against the best their opponent could possibly do. Teams have been known to spend precious minutes and even hours machining, welding, grinding, and loaning parts and tools to the very team, and the very robot, that they are set to face in the next round of play.

Community spirit makes for stronger machines, better connections, and deeply satisfying victories. This carefully maintained culture can only exist in the framework of competition, but the end result is machines that have evolved measurably across categories in the last nine years.

This real-world trial and error, which incorporates and builds on previous successes and failures, is a luxury that can’t be readily enjoyed in a traditional R&D environment, and can yield surprising results. Humanoid soccer players, for example, cartwheel down the soccer field more efficiently than they can run on two legs, something a human player wouldn’t even consider. A humanoid soccer goalie can have 360-degree machine vision, as opposed to human’s limited forward-facing and peripheral sight. What better way to refine machine-human interaction than through a robot stand-up comedy performance or via the futuristic ritual of the robot bartending contest?

Many large institutions, including Google and DARPA, have seen success with harnessing segments of the hobbyist community by crowdsourcing many solutions to particular problems, then rewarding the solutions that work the best. RoboGames does this every year, dozens of times over, and simply for the pride engendered by winning a gold, silver, or bronze medal for their team and country.

In 2009, Rodi Hartono and the team from Indonesia’s UNIKOM University were awarded the gold medal in the RoboGames Fire Fighting competition. Upon returning to Indonesia, they were given full scholarships up to the doctorate level and granted an audience with Indonesian President Susilo Bambang Yudhoyono. In 2010, team UNIKOM also took the gold, but Hartono admitted that even though only a year had passed, the challenge of beating his fellow competitors was greater.1 Mr. Hartono has been inspired to move beyond the level of student robot hobbyist and is now working on the doctoral level, with an aim of developing robotics to benefit the disabled. He hopes that business and government will recognize the

possibilities inherent in his work, and cites RoboGames as a factor in his success.

Likewise, in 2009, a team from Mexico’s Instituto Politécnico Nacional met with President Felipe Calderón upon their gold-medal bearing return from RoboGames 2009. This resulted in hundreds of schools in Mexico ramping up their robotics programs and becoming a competitive force to be reckoned with both within Mexico and internationally.

This human experience at RoboGames, plus years of watching countless machines fail and succeed, provides a unique perspective for RoboGames’ producers (which include this author). Not only does the extensive history of RoboGames point toward a continual refinement of many aspects of the field of robotics, RoboGames has also had an active hand in promoting science and technology among amateurs as well as cultivating professionals.

By encouraging sportsmanship, innovation, fun, and a love of robotics among all ages and nationalities, RoboGames stands in the unique position to harness the power of the people participating in the event, and the ideas and implementations they can bring to the worldwide robotics community.

Simone Davalos is a robot builder, writer, educator and event producer. She co-founded RoboGames with David Calkins in 2004 and consults from a robotics perspective for outlets that include Red Bull, Core77 (an online design magazine), and the monochrom arts group in Vienna, Austria. She has worked with The Long Now Foundation, a non-profit devoted to long-term thinking, and on large-scale fire and industrial machine arts with The Flaming Lotus Girls and Survival Research Labs. She currently is a development officer for the Robotics Society of America, and also works for Laughing Squid, an international arts, culture, and technology consortium.
REVOLUTIONIZING THE GLOBAL SUPPLY CHAIN:
How fleets of mobile, continuously-learning robots are optimizing the operations of our world’s top brands

By Dave Munichiello

Technology enables almost every facet of our lives, helping us become increasingly more efficient, more connected, more adaptable, and more aware of the world around us. One of the last frontiers to be substantially optimized by modern advances in hardware and software technology has been traditional warehousing in the global supply chain. These facilities are still full of static shelving, laced with old conveyors, and staffed by hiring loads of temporary workers to run around picking orders.

A growing set of distribution centers (DCs) are giving us a preview of the “supply chain of the future.” Walgreens, Staples, Office Depot, The Gap, and Saks 5th Avenue are among the companies whose distribution centers have adopted a new technology provided by Kiva Systems, a fast growing robotics and software company based out of Boston, MA. The technology, a powerful combination of robotics and sophisticated (yet elegant) algorithms on an ever-adapting code base, is moving t-shirts, pens, pharmaceuticals, high-heels, toys, medical devices, and dresses around warehouses in increasingly efficient ways. These supply chain robots address a key flaw in the distribution aspect of the standard business model. Inside a traditional warehouse there are three fundamental activities taking place: picking, packing, and shipping orders. All three share similar problems: slow speeds, inflexibility, single points-of-failure, inaccuracy, and lack of predictability. Those problems go away in a Kiva world, as the same algorithms used to dynamically route packets on a network or defragment a hard drive can now be applied to the movement of inventory around a warehouse. These advances make each worker up to four times more productive and leave the heavy lifting, navigation, and complicated efficiency management to the robots.
Traditional Distribution Center Challenges
As more brick and mortar stores turn to the web as an equally important storefront, businesses are pushing their supply chain to keep up with the rapid change of offerings while maintaining cost effective, efficient operations, and minimizing operational risk. A traditional DC is made up of thousands of square feet of concrete flooring with endless aisles of inventory. Products are stored on static shelves, often for retail store restocking or web order fulfillment. Many DC operations use a manual process for materials handling where workers walk up to fourteen miles per day through aisles of inventory shelving, putting merchandise into their carts. Other warehouses “automate” this process using conveyors or carousel systems similar to the types of systems seen at airport baggage claims. This form of automation often involves miles of bolted down metal and rubber equipment in winding patterns.

The manual process is slow, inaccurate, and expensive (requires many workers), while the conveyors or carousel systems require complicated installations, are inflexible to modifications in product shape and size, and are vulnerable to single points-of-failure. Further, changes to permanent fixtures (like reconfiguring a conveyer system to accommodate a new workflow or expanding the size of the available storage) typically require significant disruption to ongoing operations.

In the old world, if a retailer who previously sold sneakers decided to expand its product offerings to include apparel and sporting equipment, they may have to scrap their tilt-tray sorter (carousel) for a more manual operation. Worse yet, they may have to run two parallel operations for both sets of goods. Either option is time consuming and expensive, making it difficult to respond quickly to changes in market demand.

eCommerce Fulfillment Challenges
Today’s point-and-click world leaves retailers and eCommerce providers competing aggressively for sales. In this competitive landscape cost alone is no longer enough of a competitive differentiator. Internet retailers must look for other ways to convince online shoppers to select their products over another site that offers the same product at the same price. Vast merchandise selection, item availability, and shipping options suddenly have newfound influence on the consumer decision-making process.

How does this rapid movement towards instant eCommerce impact the distribution and fulfillment
side of a business? While a digital storefront is easy to update with new products overnight, there are thousands of square feet of cinderblock and concrete with rows of product that are not as easy to adapt to the increasing demands of direct to consumer (DTC) fulfillment. Business models are evolving quickly to capitalize on consumer preferences of their online shopping experience. Yet, traditional distribution centers struggle to adapt to these changes quickly enough.

Kiva Systems set out to address the challenges of both traditional DCs and the eCommerce movement nearly eight years ago and has been able to apply cutting-edge robotics and software technology to deliver a highly cost-effective, efficient, flexible, redundant, survivable, and scalable model for modern warehouse operations.

Enter, Robotics and Software

Using a fleet of mobile robotic drive units, moveable shelves, work stations, and sophisticated, decentralized control software to automate the pick, pack, and ship processes, Kiva Systems delivers a solution suitable for the unique challenges of modern fulfillment. It eliminates wasteful walking up and down warehouse aisles and allows operators to work from customized work stations, leaving the laps to the robotic drive units.

Mobile robotics for warehouse automation incorporates hardware and software technology to process orders of all sizes. This is different from other automated storage and retrieval systems because it is an integrated inventory storage, quality control, and order fulfillment system all in one. Inventory is now routed (tracked, stored, sorted, and moved) around a DC like packets are routed on a network. To pick orders, operators stand at stations around the perimeter of the building while inventory is stored on mobile shelving racks, called pods. These pods are arranged in a grid pattern in the interior of the building; when an operator requires an item for an order, a mobile robot brings the pod containing that item to the worker’s station. The worker picks the items they need out of the pods and places them into the orders they are working on. Once the items have been picked, the mobile robots return each of the pods they are carrying to a storage location on the grid floor (which is frequently different than the one it picked the pod up from). Each worker is usually supported by 5-10 mobile robots so they are kept continuously busy filling orders. For operations with multiple workflows such as store restocking and DTC order fulfillment, mobile-robotics can easily run each activity at the same time, under one roof. This includes functionality such as order picking, shipping, inventory cycle count, returns, and customization such as giftwrapping.

Because of its portability, mobile-robotics is faster and easier to install than other traditional automated solutions. In fact, a Top 100 Internet retailer was able to pick up and successfully relocate its entire Kiva system — inventory and all — from one warehouse to another in just 48 hours. Operators logged-out of their workstations on Thursday night in one location and 48 hours later, seamlessly logged into their...
new workstations 15 miles away to finish the week’s orders. This same activity would have taken months to complete with any other type of automation. With the ability to set up and transport an entire warehouse of inventory quickly for commercial purposes, it’s easy to imagine this same functionality applied as solutions to other global challenges. In military operational settings, every minute of response time matters. Operations like disaster relief could be enabled by using mobile-robotics to create temporary warehouses in hours; storing, sorting, and dispatching much-needed food, medical supplies, and technology in real time. Further, extreme climates, constant motion, and exhaustion serve no threat to robotic productivity in a warehouse environment.

**Conclusion**

Mobile robotics empowered by cutting-edge software has many unique benefits. It delivers breakthrough performance and revolutionizes an industry by solving real-world business challenges:

- Each element of the system is flexible and moveable, making it easy to set up and add inventory at any time without a permanent commitment.
- Mobile robotics is two to four times more productive than other pick, pack, and ship automation approaches because it eliminates wasteful walking, and instead the robots appear with the inventory that is needed when it’s needed.
- Orders filled using mobile robotics are 99.99 percent accurate due to barcode scanning and multiple methods for confirming quantity and product accuracy, including lasers that point pick workers to the goods, and lights that show workers where to place picked inventory.
- Orders can be processed in under 15 minutes from the time the order is submitted to when the labeled package is sitting on a delivery vehicle ready to go.

As Kiva’s technology spreads throughout the global supply chain creating more robust, dependable, redundant, survivable, and efficient distribution centers for large corporate players, the potential for it to enable military operations becomes increasingly clear.

Dave Munichiello is the Director of Professional Services at Kiva Systems with full P&L responsibility for a 30-person team deploying (configuring, integrating, installing, testing, training) systems worldwide. He is a former United States Air Force Captain (communications & intelligence) and served in a Joint Airborne Unit leading teams to arm elite Joint Special Operations Forces around the world with cutting-edge technology. Dave previously served as an Aide-de-Camp to the Four-Star General commanding USAF in Europe, NATO Air Forces, and ISAF. He received B.S. degrees in Computer Science and Math from Emory University and an MBA from Harvard Business School.
The MARCbot: The Army Program that Revolutionized Robotics for Patrol Warfighters

by William J. Cohen and Ken Zemach

Introduction

In Iraq, sometime during 2003, the threat of Improvised Explosive Devices (IEDs) used against U.S. and coalition forces began to grow significantly and resultant deaths and injuries became frequent. IEDs became the most common and effective tool of the insurgents and, for a moment, we were surprised. There was nothing fancy about the tactics and nothing particularly advanced about the technology, but insurgents leveraged an effective way to kill and injure warfighters. The stories are myriad: IEDs in boxes, trash, gas cans, dead animals — laying there in the road and triggered in various ways. Initially IEDs were made from old artillery shells that were easy to procure in the immediate post-invasion Iraq. The types of IEDs continuously evolved throughout the U.S. combat involvement in Iraq to include homemade explosives and horribly effective EFPs (explosively formed penetrators). IEDs were the first truly asymmetric, evolving, effective, and enduring threat of the Iraq conflict with enormous associated human and capital costs.

This article is about the Multi-function, Agile, Remote-Controlled Robot (MARCbot) introduced as an inexpensive, mission-specific robotic platform developed for the inspection of suspected IEDs or suspicious materials throughout the urban and rural environments of Iraq. It was developed with the intention of providing route clearance, patrolling, and convoy warfighters an asset that could improve positive identification of IEDs at a time when that need was both critical and generally unaddressed. The resulting benefits provided warfighters with standoff from potentially deadly devices, the ability to summon specialty bomb disposal personnel with a greater certainty as to the need, and allowed patrols and convoys to push forward with their critical missions. Over 1000 production MARCbots were manufactured by Exponent, Inc. for use in Iraq, and later, in Afghanistan.

The Role of the U.S. Army Rapid Equipping Force

In 2002, the Vice Chief of Staff of the Army, GEN John M. Keane, heard that warfighters were sometimes exploring caves in Afghanistan with a rope tied around their waist, the same thing many “tunnel rats” did in Vietnam. He asked Army COL Bruce Jette to lead a response to this allegation and perhaps identify some sort of robot that could do the job instead, thus exposing warfighters to less risk.

To help mitigate this problem, Exponent was asked to create a theater-capable wearable computer with helmet mounted eye piece display to control the robot and support the mission. In less than two months, Exponent engineers and Army personnel were exploring caves in Afghanistan with robots. Because of the success of this mission, GEN Keane initiated the creation of the U.S. Army Rapid Equipping Force (REF). Its mission is to provide warfighters with critically needed capabilities in the shortest possible time frame. Exponent became the REF’s main engineering partner to help assess capability gaps and provide engineering prototyping both in and out of theater for nearly eight years.
A New Mission to Combat IEDs

By 2004, REF had established an in-country presence in Iraq with Exponent labs. As the IED threat in Iraq increased, so too did the horrific stories about soldiers dying while investigating suspicious objects in the road (be it an old tire, dead dog, burlap sack, or even a hole that was the scene of a previous IED blast). Exponent began to engage with warfighters on their operational problems, and kept hearing the same thing. When asked why they would just walk up to something they suspected might kill them, warfighters would often respond, “What else are we supposed to do?”

The choices at the time were very limited. If you suspected that something was an IED, you could: walk up to it and inspect it; drive by it slowly and inspect it; drive by it quickly and hope it didn’t blow up; shoot at it and see what happened; or use binoculars to view it — all of which were either dangerous or ineffective. The other option was calling the Explosive Ordnance Disposal (EOD) to investigate it with their specialty robots or other methods. However, at that time, EOD response times were often measured in hours, during which the road had to be closed, and insurgents could freely set up attacks using mortars and rockets. For warfighters on patrol whose job it was to keep the roadways open and safe for travel, none of these options were sufficient or particularly safe.

Robots for Route Clearance: A New Concept

In the early days of the Iraq war, the average patrolling unit did not think that they could get access to any sort of remote detection device. The now much-utilized Buffalo vehicle consisted of a fleet of two, and it took years to assemble enough Buffalos to service the need. This led Exponent and the REF to repurpose the iRobot PackBot Scout robots from Afghanistan to Iraq for use by everyday patrol units. In early 2004, 22 of these robots were made available in Iraq for investigative purposes.

The rules for usage were simple: non-EOD personnel were not allowed to “mess” with suspect devices. However, using a robot to visually inspect a suspicious object often allowed warfighters to confirm that it was not a threat, and the mission could proceed. In the case when an IED was found or at least still suspected, then EOD would be called. This, in turn, greatly decreased the quantity of calls to EOD, freeing them up to handle more likely threats, and reducing their response time.

Creating the First Small Robot for Patrol Soldiers

By the middle of 2004 it was clear that small robots could be useful, but the price tag, limited inspection capabilities (no elevated camera), and limited availability of other appropriate robots made it an unlikely and insufficient bulk purchase. At the request of the REF, Exponent prototyped a small remote controlled device for the mission. The final product had very high reliability rates in theater, and was purpose-built for the threat and environment. The idea was that, when the heat was on, a warfighter could deploy the robot in under one minute.

These initial few robots, placed with the units who had the need and mission, were tremendously successful. For instance, the very first prototype was reported to have confirmed over 30 IEDs on the notorious Airport Road between the Baghdad Airport base complex and the Green Zone. IEDs proved to be one of the most dangerous and disruptive tools in the insurgent’s arsenal and every day in Iraq, dozens of IEDs continued to disrupt convoys, destroy Coalition assets, and maim and kill U.S. troops. The MARCbot immediately proved to be an extremely critical tool in this fight. The 2nd REF Director, COL Greg Tubbs, decisively initiated the notion of small robots for patrols and ordered the first large batch to be distributed throughout Iraq as well as negotiating their repair and support by the Robotic Systems Joint Project Office.

Applying In-Theater Technology Experience to Shape Military Product Development

By 2004 Exponent had worked with and supported a number of robotic platforms. In-theater development and supporting technology proved critical in the development of the MARCbot, driving several design principles that were essential for the MARCbot’s success:

- Design the robot to do only one task, and that task must be something that is repeated often. Any
The final product had very high reliability rates in theater, and was purpose-built for the threat and environment.

functions that broaden the range of capabilities outside of the core mission only serve to add complexity, reduce overall system reliability, add unnecessary cost, and increase user training requirements and potential confusion under pressure. A user must be able to find the robot in its box and successfully operate it in less than a minute.

- Specifically do NOT design in other features, systems, and capabilities that are only tangential to the mission. For instance, GPS was specifically rejected as an option due to Exponent’s in-theater experience with the GPS system, capabilities, and issues with other robotic platforms.

- Absolutely reject any control system that has buttons or controls that are not central to the primary mission of the robot (e.g., a laptop). By the time of design, Exponent had several years of in-theater experience supporting several types of robots that were controlled by both wearable computers, and later by laptops. The use of computers to control robots resulted in roughly three times the number of support issues over and above the support of the various robots themselves.

- Use standard systems. In this case, the use of military-standard x90 batteries was required because warfighters nearly always have access to them.

- Absolute minimization of technology and components for reduced system maintenance and lower costs.

Benefits of the MARCbot as an Asset to Patrol Soldiers

Over the next few years, additional features were added to improve the performance of these robots. Remote antennas allowed warfighters to operate the robot from within the armored environment of their vehicle and to see what the robot sees from safe distances. The simplicity of the system allowed a warfighter to receive the robot and, without complex training, be able to fully operate it nearly immediately. This proved enormously helpful during a time when warfighters in need were scattered around Iraq, but trainers were not. The MARCbot was also the first military robot asset to run exclusively from military batteries, and runtime topped almost six hours from a set. Since the fielding of the MARCbot, both the Packbot (iRobot) and Talon (QinetiQ) EOD robots have been upgraded to ensure that they operate on military standard x90 batteries as well.

Estimates from the field indicated that the MARCbot was used successfully on thousands of patrols, making determinations about hundreds of suspicious items, and saving the lives of U.S. warfighters. In the end, Exponent and the REF proved that with the MARCbot on patrol, there was never a reason that a warfighter ever had to “kick the box” again.

Dr. William J. Cohen is a Principal in Exponent’s Technology Development Practice. His consulting practice in Industrial Engineering specializes in the design, adaptation, and implementation of technology to solve operational problems for the U.S. Military. This work involves evaluation of capability gaps for deployed soldiers, technology assessment and testing, and iterative product design. Over the course of a year, Cohen was chief proponent for the design, testing, training, repair and fielding of the MARCbot—culminating in the delivery of nearly 1000 of these proven, life-saving devices to the U.S. Army.

Dr. Ken Zemach has spent over two years overseas, working in both Iraq and Afghanistan solving problems for the U.S. military. Zemach was one of ten recipients of the U.S. Army’s Greatest Inventions award for 2003. Solutions include a preferred passive under armor cooling method, a down-well imaging system, a remote monitor and power solution for a weapon mounted thermal imager, a wearable antenna system, a power supply solution for a high end thermal imager for base security, an inexpensive method for foreign phrase translation, and a practical method for harvesting untapped energy in military batteries for long duration missions. Currently, Zemach’s scientific consulting practice specializes in the application of appropriate technology to solve current problems for both the Military and consumer marketplace.
THE FUTURE OF ROBOTIC AIRCRAFT

By Warren Soloduk and John Klinger

Figure 1

Robots of all kinds are now prevalent in military, law enforcement, industrial, commercial, and residential applications, and many of us can remember when such uses were confined to the pages of science fiction publications. During the past two decades, there has been a tremendous growth in the use of Unmanned Aerial Vehicles, initially led by the Military and Intelligence Communities, and now by law enforcement, commercial businesses, and even the entertainment industry.

Fueled in many cases by the reduction in the size and power requirements of computers, the improved reliability of GPS systems, the use of lightweight, high-strength composite materials, and higher bandwidth communication systems that allow for real-time viewing of high-quality video, UAVs of all sizes are being used today for intelligence gathering, surveillance, reconnaissance (ISR), identifying and attacking targets, search and rescue, firefighting, and film-making. As the willingness to use UAVs has grown, the reliability, effectiveness, and autonomy of these systems has also improved. If the current trends continue, unmanned and optionally manned vehicles will assume more of the roles that have traditionally required piloted aircraft such as pipeline and other infrastructure surveillance, chemical, radiological, biological detection and measurement, and advanced military missions such as air supremacy and close air support for ground operations.

DARPA is demonstrating the potential for robotic aircraft to be used for Persistent Close Air Support (PCAS) by converting an A-10 aircraft into an optionally piloted vehicle, already nicknamed the “Robo-hog.” In this program, the A-10 will act as a surrogate to help define system requirements for the USAF’s next generation of unmanned aircraft. A major goal of DARPA’s PCAS project is to evaluate the potential...
for reducing response time from when air support is requested to when the attack is conducted to a matter of minutes by both streamlining and automating many aspects of the current process, including removing the human pilot from aircraft sorties. DARPA’s program will also evaluate the ability of a robotic aircraft to address mission support requests from more than one ground source for multiple rapidly moving targets, with the ability to make last second changes. The program will also feature an automated targeting system that will integrate various communications systems with the aircraft and ground station’s automated control systems. Figure 1 shows a photo of one of Proxy Aviation System’s optionally piloted aircraft that recently took part in the Office of the Secretary of Defense for Intelligence’s Empire Challenge 2011 exercise. Two of these aircraft were equipped with government-provided advanced camera systems, and were used for autonomous and coordinated ISR missions. Figure 2 shows a schematic of the autonomous flight and cooperative engagement capabilities that were demonstrated during Empire Challenge 2011.

The current generation of UAVs and optionally piloted aircraft can stay airborne longer (in some cases more than 30 hours), can fly more precise, complicated, and highly repetitious flight paths than are possible by most human pilots, have sophisticated terrain and collision avoidance capabilities, and can carry heavier and larger payloads. While most UAVs in use today fly within a limited roll and gravitational force envelope, advanced autopilots have demonstrated the ability to control aircraft effectively while performing difficult aerobatics maneuvers. Also, autopilots are not limited by the gravitational forces that might cause a human pilot to black out.

Some of today’s sophisticated command and control software, such as Proxy Aviation’s UDMS (Universal Distributed Management System), can provide the ability for one ground operator to command, control, and monitor the status of multiple UAVs and their onboard sensors. In such systems, the operator will typically only send advanced-level commands to the aircraft that the UAVs are designed to follow with a high degree of autonomy. The UAV computer’s software is programmed to make decisions based not only on commands from the operator but also on the faults it receives from onboard systems (e.g. engine data, fuel left, communications status), and on messages and information it receives from other aircraft. In such systems, each UAV can automatically perform functions like collision avoidance, terrain avoidance, and limiting flight to specified corridors and away from no-fly zones.

As an example of advanced robotic control of aircraft, Proxy Aviation’s Ground Control Station [pictured in Figure 3] is set up to control four UAVs, two of which can be seen flying a precise path to cooperatively search a specified area. Each UAV is preloaded with one or more possible missions. Each mission has multiple phases during which the UAV is given rules to follow for making decisions about each of several “topics” (e.g. Navigation, Payload, Tasking, and Mission Flow). Examples of high-level commands that the operator might give to the UAV include changing the UAV’s mission and/or changing the current phase in its mission.

In the FLIR Support mission, shown in Figure 3, the UAV, configured with a FLIR camera, has been tasked with supporting the detection and destruction of targets that emit radiation with known signatures. The phases of the mission are Takeoff, Rendezvous, Continuous Survey, Evaluate Target, BDA (bomb
damage assessment), Hold for Landing, and Landing. The phase shown is Continuous Survey in which the Navigation topic’s profile is to perform a “Search Pattern” of a specified area. When flying this profile, the UAV checks whether any other UAVs are currently searching the same area, and if so, it will automatically subdivide the area into sub-regions, assign a different sub-region to each aircraft, and limit the search to its sub-region.

Another type of high-level command that the operator can select is to change the current profile (or topic policy) associated with one of the phase’s topics. The operator can send a command to change the Navigation topic’s profile to one of the other Navigation profiles in the system such as “Follow Route” in which the aircraft will fly a pre-specified route or “Hold-On-Point” in which the aircraft flies a specified pattern around a given point (e.g. circle, racetrack, or figure-8). During any mission phase, the aircraft is also performing actions specified by the other topics in the phase (in addition to the Navigation topic). The Payload topic’s policy in this example is Manual Scan in which the aircraft assumes that an operator is manually controlling the camera and limits commands to the camera except to turn it on. Alternatively, the operator can send a command to change the Payload policy to Scan Target and have the aircraft automatically slew the camera and cover the area ahead of the aircraft in a methodical way as the aircraft flies the pattern.

Another topic in the phase is the Tasking topic. This topic holds policies that automatically change the phase or the policies in other topics if certain events occur. In the current phase, the Tasking policy will automatically move the aircraft to the next phase (Evaluate Target) if a new target is found. In the next phase, the aircraft will slew its camera automatically to point at the location where the suspect emitting target is located and will fly to circle that location. In this phase, the Tasking policy will automatically move the aircraft to the BDA phase if the target is attacked or go back to the Continuous Survey phase if the target is not approved for an attack.

Another example of a Tasking topic policy is “CoT Tasking.” This Tasking policy is used to make the aircraft automatically respond to certain “Cursor on Target” (CoT) messages the Ground Station receives from other operator control stations on the ground. The “Cursor on Target” messaging schema has become a standard method that various disparate software programs use to communicate.
As more UAV systems become pervasive, the user community is trying to define interface standards for messages that command, control, and monitor these aircraft.

key targeting information to each other, and is an example of a standard that has contributed to the growth of UAV systems.

Proxy Aviation’s control system exemplifies the increased sophistication and autonomy being given to individual UAVs in current robotic aircraft systems. As UAV systems become pervasive, the user community is trying to define interface standards for messages that command, control, and monitor these aircraft. A goal that has been discussed with military leadership is to have all UAV systems speak the same language so that a common UAV control station can be used to control any current unmanned aircraft. The NATO standard (STANAG 4586) is still a work in progress, but represents a major effort toward this goal. Prompted by the users, most UAV systems can now implement some subset of the command options available in STANAG 4586, but the goal of a standard UAV control station remains elusive.

We believe autonomous and robotic aircraft will play increasingly larger roles in routine and dangerous missions. The reliability and safety of these systems will continue to improve dramatically as designers and operators continue to gain experience. More sophisticated software is being developed today which allow such aircraft to fly with a greater degree of autonomy, permitting a single operator to control a fleet of dissimilar UAVs as they perform a variety of complex missions. Standards are being developed which will permit these systems to speak a common language so that systems from different vendors can be made to work together effectively.

Warren Soloduk is the Managing Director of Truestone, a 300 employee Technology Services company based in Herndon, VA. His 25+ years of commercial and government service includes roles in manufacturing, engineering, contracting, project management, business development, sales and marketing, and operations management. He served as a senior officer in the USCG, has held executive positions with advanced technology companies, and has led three technology startup companies. Soloduk also served as a Director for Intelligence Community Support for In-Q-Tel, and was the President and CEO of a startup software and control systems company that specializes in autonomous control for aircraft, ground-based, and maritime platforms.

Dr. John Klinger is an Engineering Fellow at Proxy Aviation Systems. His background includes more than 30 years developing advanced aviation software for the U.S. Military. Klinger pioneered the development of mission planning software for military pilots that used map data and satellite imagery for planning missions instead of paper maps. First employed by the USAF during Operations “Desert Shield” and “Desert Storm,” this software helped initiate the transformation in mission planning that occurred in the following years. Klinger is currently leading in the development of Proxy Aviation’s UDMS software that allows a single operator to control a fleet of unmanned aerial vehicles. He received his Ph.D. in high energy physics from Cornell in 1978.
NEW DEVELOPMENTS AND FUTURE PROSPECTS FOR SMALL UAVS

by Todd Hylton

In December 2006, the Defense Advanced Research Projects Agency (DARPA) launched the Nano Air Vehicle (NAV) program to develop hand-sized air vehicles and explore their capabilities. NAVs may have utility for operations in locations that are not readily accessible using other robotic platforms, especially those involving obstacles such as buildings, walls, windows, tunnels, towers, and other vertical or steeply angled surfaces. This article describes the main product of the NAV program, a robotic hummingbird, and outlines the ongoing technical challenges to the deployment of such small aircraft in these challenging environments. The author of this article managed the program for DARPA from 2007 to its conclusion in January 2011, as well as other programs mentioned in the article.

The goal of the NAV program was to develop flight-enabling technologies for small aircraft and to demonstrate an air platform with the potential to perform useful indoor and outdoor military missions. The first phase of the program explored four different flapping-wing and rotary-wing propulsion concepts on which to base the prototype vehicles. Inspired by the agility and appearance of biological hummingbirds, in the second phase of the program AeroVironment (AV) of Simi Valley, CA was selected to develop a hummingbird-like NAV. This selection entailed a host of novel and difficult problems. Simply put, because such a vehicle had never been built before, there was little in the way of useful engineering practice or design tools to guide the development. Further, the severe constraints of size, weight, and power required
a system in which the components were so closely coupled that the common “divide and conquer” system engineering strategy was of limited utility. The challenge was met via a substantially heuristic approach including the development of numerous test benches, flying prototypes, novel mechanical and electrical subassemblies, and analytical tools conceived and executed by a small, artful, and capable engineering team responsible for every aspect of the project.

Nature’s hummingbird is a remarkable flyer. No other birds compare in their ability to hover, transition rapidly between hover and fast forward flight, and to maintain stability in flight with reference to a target object. Further, although weighing only several grams, hummingbirds are able to fly in winds that easily overwhelm familiar toy aircraft of much greater size. Capturing such flight capability is a first requirement for the successful deployment of an NAV scale system in most defense or intelligence applications of interest. Figure 1 shows the final prototype developed under the NAV program. At just 19 grams (about one AA battery) with a wingspan of 6.5 inches, this robot hovers, moves easily in forward-backward-sideways flight, pirouettes, and flips [Figure 2] using only the wings for both propulsion and control. In forward flight its top speed easily exceeds the initial program goal of 5 m/sec (11 mph) and can recover from gusts of 2.5 m/sec. A minimalist version can hover in excess of 11 minutes. The prototype also contains a miniature camera that relays video to the pilot’s ground station. Although stated as a simple summary here, these numbers are the product of an extensive and difficult development effort and presage a new ability to engineer air vehicles: for the first time we know how to build lightweight, hovering, flapping wing air vehicles precisely controlled by modulating the wing dynamics.

The control of the vehicle through the wings and its integration with the propulsion system stand out among the various achievements of the program. The wings of a hummingbird reverse shape in the transition from fore to back stroke to generate lift in both stroke directions, and by making only minute changes to the symmetry and shape of these strokes, the hummingbird creates large aerodynamic forces and torques that enable it to rapidly maneuver. In order to achieve a similar capability in the NAV robot, more than 300 wing designs were tested in combination with numerous different wing-drive motors and transmission mechanisms to optimize on competing needs for lift, durability, and acoustics. Maneuverability was achieved with an elegant actuation system that provides modest deflection to the roots of the wings to achieve large aerodynamic effects. Figure 3 shows a frame from the NAV
hummingbird in flight with a corresponding image from the on-board video camera. Several videos of the robot in flight are posted on YouTube (search “DARPA Hummingbird”).

The NAV prototype includes onboard active stabilization via inertial sensors (also known as inertial measurement units or IMUs) providing feedback to an onboard micro-controller that drives the wing motion. GPS navigation, which is common on larger UAVs, was not an objective of the program since the operational environments of interest are poorly suited to it. The robot is remotely piloted in a manner similar to that employed by most radio controlled aircraft. This combination of onboard IMU stabilization and pilot control were adequate to achieve the primary goals of the NAV program, but operational systems will require additional capabilities. The following paragraphs describe the further challenges to be overcome and some promising as well as speculative approaches to address these challenges.

Remotely piloting a small, unseen aircraft using only a video image from a fixed field of view camera mounted on the vehicle is extremely difficult even for the most experienced pilots. Because IMU-based stabilization for these small vehicles is only effective for very short times (typically <1 sec), the pilot must constantly correct for the “drift” in the air vehicle. In the confined environments of interest in the NAV program, this means that the pilot cannot afford even small periods of inattention or the vehicle will crash. Further, it is extremely difficult to judge the distance and time to obstacles and nearly impossible to respond effectively to a wind gust even if the air platform has ample control authority. In short, remotely piloted, operational vehicles must be able to autonomously hover in place, avoid obstacles and compensate for gusts. Fortunately, solutions are emerging involving combinations of optical image processing techniques and range measurement techniques using lasers, acoustic, or RF probes. As an example, arrays of simple image processing sensors capable of detecting the optical flow associated with the movement of an air vehicle on which they are mounted have been demonstrated under another DARPA program. Figure 4 shows such a system built by Centeye, Inc. integrated on a modified hobby helicopter. This helicopter can autonomously hover-in-place, avoid large obstacles, and respond to perturbations in its flight. A similar capacity has been achieved by Draper Labs on a quad-rotor platform using a large angle camera and a vision tracking system. In combination with an extremely agile air platform like the NAV hummingbird, these and other techniques promise the first generations of small, teleoperated, mission-capable air robots for use in GPS-denied, confined environments with difficult air conditions.
For the first time we know how to build lightweight, hovering, flapping wing air vehicles precisely controlled by modulating the wing dynamics.

An even greater operational challenge for these small air vehicles is radio communication to and from the pilot/user. Small air vehicles imply small RF power budgets and small antennas while confined environments imply substantial RF attenuation through walls and other obstacles. If the separation between the user and the air vehicle is modest and the obstacles few, then these communication challenges can be addressed using existing technologies. On the other hand, in many conceivable operating environments, communication with the vehicle throughout the entire mission may be impossible. Such situations will require much greater on-board autonomy of the air vehicle than what was discussed in the prior paragraph. In essence, users will need to instruct or program the mission objectives onto the vehicle — perhaps locating a target or mapping a building — have the vehicle perform that mission with minimal communication, and report results when it returns. Such capabilities severely tax the small computational capacity that these vehicles can carry. The DARPA SyNAPSE program is addressing this problem through the development of “neuromorphic” electronic hardware, which is much better suited to large scale problems in sensory perception, sensory fusion and motor control than conventional computing hardware. Neuromorphic hardware mimics the structure and function of the brain by using broadly distributed neuronal processors and synaptic memories communicating with simple spike-like signals. The first prototype systems/chips of the SyNAPSE program are scheduled to be delivered in early 2013 by the performers IBM and HRL Laboratories.

In conclusion, the DARPA NAV program successfully demonstrated a small, lightweight and agile air vehicle inspired by the hummingbird. The first defense and intelligence applications of this vehicle and others in its class will be enabled by integration of recently developed autonomous control capabilities. Ongoing developments in specialized electronic systems may lead the way to much greater levels of autonomy in the near future.

Dr. Todd Hylton joined the Defense Advanced Research Projects Agency as a program manager in May 2007. His program interests include neuromorphic electronics, machine intelligence, novel computational architectures, novel electronic components, and small unmanned systems. He holds a B.S. in physics from M.I.T. and a Ph.D. in Applied Physics from Stanford University.
RESCUE ROBOTICS: THE FUTURE OF AN EMERGING FIELD

An IQT Interview with Dr. Robin Murphy

In a recent interview with IQT, Dr. Robin Murphy, founder of the field of Rescue Robotics and professor at Texas A&M University, discussed the important role robots can play in search-and-rescue efforts. She also offered insight as to what needs to be done to make sure these life-saving robots are ready and available to respond to disaster situations around the world.

Rescue robotics is a relatively new discipline. Can you give us a quick background?

We’re now approaching the tenth anniversary of the first use of robotics for search and rescue, which was at the World Trade Center following the September 11, 2001 attacks, though they’ve been talked about since the early 1980s. In the 90’s we began to see some small robots, such as Sojourner (the Mars Pathfinder) and there was a push to begin to make robots smaller. In 1995, two big events happened: the Kobe earthquake in Japan and the Oklahoma City bombing in the U.S. These events made some people realize if you could have gotten smaller robots into the rubble after those disasters, you might have been able to get survivors out.

Rescue robots operate in three environments: ground, marines, and aerial, and all are needed for response. For ground robots we’ve seen wonderful advances, particularly for military applications and IEDs, but using robots for search and rescue is actually harder. Rescue robotics is not done on flat ground, you’re going into rubble — so it’s incredibly difficult.
Aerial vehicles are difficult too in terms of navigation and maneuvering. Similarly, we have problems with marine vehicles. Even in shallow littoral regions we’ve got tides, currents, and turbidity. It makes for a set of fascinatingly hard problems.

How do you address the unique mobility and power challenges of rescue bots?

Our research has shown that operators are thinking about mobility and navigation only 44 percent of the time, and the rest of the time is spent trying to figure out what they are looking at. Because of the nature of disaster scenarios, there’s not a lot of use in planning the optimal plan. These are an extraordinarily difficult environments to see what you need to see, in part because every disaster is different. You don’t know what you need to see until you see it.

As you see with a lot of military applications, there’s remote presence, which means you’re using the robot to project yourself in real time and get into a place that you can’t be physically. That place could be 3000 miles away or it could be 30 feet away but you can’t fit there. We’re making the whole system smarter and autonomous, but the robot needs to do the work. Not a taskable fully anonymous robot, but a scenario where we can share the autonomy.

Regarding power, if you have more power you can blast radio waves and do things wirelessly you couldn’t do before. In certain cases you need to use tethers, but in general we haven’t seen power be a huge driving problem. Instead, we find that the sensors are a problem. They’re too big. In these environments, dirt and water get on them. When we were going through rubble in the Crandall Canyon mine disaster we had 8 ½ gallons of water and debris coming through as the robot was being lowered through the bore hole. We found that the front camera would be quickly useless after getting in there. What was surprising to the manufacturers and to us is that the upper camera also got fouled. The challenge: how do we keep these things clean?

Another aspect of this challenge is that we’re seeing so much more now with the addition of different kinds of sensors. It’s the mindset that two heads are nine times better than one. What we’re seeing with our research is the assumption that humans can absorb all of this information being relayed by the sensors, which is not always the case. People might not complain but that doesn’t mean the performance is high. In fact, on a performance level they’re not doing as well as they think. It would be more helpful to look at one thing at a time. You can look at the vision, then stop and do the thermal, and then go back to the vision, etc.

How do we increase adoption of search and rescue robots?

New Jersey Task Force 1 is the only team in the U.S. that has a rescue robot. It goes to show that it’s all about the money. It turns out you can’t buy robots in the public sector unless you have the money. If you are relying on a federal grant, those grants usually have preapproved lists of things that the money can be used for. States typically mirror the list for items that federal grant money can be used for, and rescue robots aren’t on the federal list because the standards haven’t been agreed on yet. We expect the standards to be completed soon, but where’s the federal grant to provide money for it? Something needs to happen for people to get interested in rescue robotics and municipalities need to have access to money to buy the systems. When the National Institute of Justice declared that you can’t be considered a bomb squad unless you have a bomb squad robot, everyone in our industry got really excited about it. But they also set aside a pot of money for all of these municipalities and provided a list of robots that met the standards and requirements. That really engaged the industry and led municipalities to make requests for additional features.

There is also a serious challenge with regard to the frequency of use. The military uses IED robots up to four to five times a week for screenings — it’s part of the day job. The rescue robot is part of the day job but it’s not as regularly used. For responders, three days of training is a huge investment of time, which means we need to make the robots even better so they can be used effectively even by those who use them infrequently.

We also know that when you have a new technology, the way to get it adopted faster is allowing customers
to make requests, and change it more. But in this case, they can’t tell you how they’re going to use it — it’s new! They’re going to find some killer app as they use it and will want to request it for the design. Industry can help with accommodating these requests.

Can you share a success story?

Absolutely. We were recently in Japan following the massive earthquake and tsunami, where we led a team using Remotely Operated underwater Vehicles (ROVs) to inspect critical infrastructure and look for bodies and underwater victim recoveries. We ended up using an ROV originally developed by robotics company SeaBotix, on behalf of the British government. The British had the funding, but as the client they made a request: they wanted regular personnel to be able to take the machines on a trip, and be able to throw them in the water and have them work. They wanted the robots to work, be reliable, get in there and grab somebody. Even though its almost identical to another vehicle they make, the company made it a little beefier — they made it so tough a person can’t screw it up — and took away some of the options. There was another vehicle with better sonar, but that was a bit bulky and hard to use. When we were in Japan, we used the one that was built to set up in ten minutes and not break.

I understand that on 9/11, you mobilized your team and made it from Tampa to New York in less than 24 hours. How do you ensure your team is prepared in case of disaster?

We left for New York within four hours on September 11. Other team members stationed in the northeast were there in six hours. We stay at a constant state of readiness. Our cache doesn’t always cover everything in a disaster area, but we also have Roboticists Without Borders. This organization provides member companies with training beforehand, including an opportunity to try out the robots to see if it’s a fit for a given disaster.

During the Japanese earthquake and tsunami we realized we couldn’t use ground robots. We needed to get underwater to examine and restore the critical infrastructure. We settled on a set of four different ROVs to bring out there, only one of which we owned; the others came to us from Roboticists Without Borders member companies. We try to do this mix-and-match to respond to the disaster because they’re all unique.

Final Thoughts

These robots are good enough now; we tend to see a horizon effect, people thinking, “they’ll make a perfect robot.” There is no perfect robot. Robots are useful, they just need to get out there, get their hands dirty, realize what works and what doesn’t. It’s not perfect, but we can’t afford to wait for perfection. ♩

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A NEW APPROACH TO PORTABLE POWER: High Efficiency, Flexible, and Lightweight Solar Fabric

A technology overview from IQT portfolio company Semprius

The sun generates an enormous amount of energy which blankets the earth with 1,000 watts per square meter for long periods of time. In some remote parts of the world it is the only practical source of power. By designing a high efficiency, flexible solar fabric that is compact and lightweight, portable energy can be provided in sunny remote locations to power ground-based, mobile, and aerial electronics. This paper describes why this is important, what applications can benefit from such a material, and how the solar fabric works.

Introduction

Photovoltaic (PV) system installations grew at a phenomenal rate of nearly 100 percent last year and have grown at a compound annual growth rate of 41 percent per year during the past decade. This year overall PV shipments are expected to exceed 20 gigawatts. A vast assortment of different technologies are available today – from traditional flat panels based on single-crystal and multicrystalline silicon to promising new thin film panels based on cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) to the latest low cost, high performance concentrator photovoltaic (CPV) systems. However, most of these technologies are based upon large, relatively heavy and rigid modules that are not portable. In order to produce a lightweight, flexible solar module, several companies have explored the use of organic PV in a flexible form factor, but the efficiency is relatively low at 5-8 percent and the lifetime of the material is limited. Amorphous silicon is a thin film technology that can be flexible and is in actual use in the field, but again the efficiency is quite low at 8-12 percent. CIGS has the potential to be much higher in efficiency at 11-14 percent, with a laboratory demonstration of 20 percent. However, this material is very sensitive to moisture ingress so a flexible and lightweight solution is quite challenging if reasonable lifetimes are expected.

The Semprius approach uses high efficiency III-V compound material (e.g. GaAs), which has been used for decades for high frequency transistors,
LEDs, lasers, and space-based solar cells. Solar cell efficiencies are already greater than 40 percent under high concentrations and the reliability of these devices can be 25 years or more. Furthermore, by using a patented new manufacturing technology called micro-transfer printing, only the thin, flexible, active layer of the device is printed onto a flexible polymer to produce a solar fabric that has an ultra-high power-to-weight ratio — much higher than any other available technology.

**The Challenge**

In order for flexible solar fabric to be practical for high performance field use, the following requirements must be met:

1. The fabric must be environmentally sealed to protect the cells from dirt and water.
2. The top polymer layer must be flexible, have low moisture permeability, and be transparent in the wavelengths of interest (400-1500 nm).
3. For rapid deployment and stowability, it must be lightweight, flexible (capable of a radius of curvature of one inch so that it can be rolled up like a map), and robust.
4. The cells must be interconnected with a flexible, high conductivity material.
5. For discreet operations, it must be small, highly efficient, and capable of hosting coatings that form an effective camouflage.

The result is a fabric with a very high power-to-mass ratio. This ratio is referred to as *specific power* and is measured in W/Kg. The benefits of such a solar fabric are enormous:

- Reduced battery consumption and disposal.
- Fuel savings associated with transporting batteries and fuel used to charge batteries.
- Reduced weight, leading to increased mobility.
- Extended length of field operations.

**Applications**

There are numerous applications for highly specific power solar fabrics. When carried during ground-based operations, solar fabrics in backpacks allow users to power electronics and re-charge batteries. Remote monitoring stations can be powered with small, flexible solar fabrics that can wrap around the instrument in a compact, discreet way. Lightweight solar fabric stretched across the top of the wings of manned and unmanned aerial vehicles can provide power with reduced fuel consumption, which can significantly extend the length of certain missions. Next generation airships can be completely powered by solar fabric. When used on low earth orbit satellites, a high efficiency, lightweight solar fabric could significantly reduce launch costs. And, it is reasonable to suggest that even more applications will come to light as thought leaders become more aware of the capabilities of this new material.

**Semprius’ Approach**

Semprius produces the world’s smallest solar cells, resulting in numerous performance and cost benefits when used in CPV applications. Small cells provide benefits to flexible solar fabrics as well. The use of small, thin solar cells is made possible by a micro-transfer printing technology invented by Professor John Rogers at the University of Illinois and subsequently developed by Semprius for commercial applications. Figure 1 is a conceptual drawing that shows how it works.

The process starts with the source wafer, which consists of a multi-junction III-V compound semiconductor-based solar cell structure grown on top of a GaAs substrate. As part of the structure, a sacrificial release layer is epitaxially grown between...
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the solar cell structure and the substrate. This layer will be subsequently etched away at the end of the wafer processing steps to release the thin cells (6-10 μm thick) from the substrate.

The elastomer transfer stamp is designed with many small posts on the bottom side. Each post is the size of the solar cell that it will pick up. The pitch between the posts is designed to match the spacing of the solar cells on the source wafer. To transfer cells to the solar fabric, the transfer stamp is brought in contact with the source wafer such that the posts touch the solar cells intended to be picked up. The stamp is then quickly raised and because of the strong van der Waals forces between the cells and the elastomer, the cells are lifted off of the surface of the source wafer. Next the stamp is moved laterally and brought down in contact with the solar fabric where the cells are printed onto the surface. Many thousands of cells can be printed simultaneously using this cost-effective method.

Finally, the cells are interconnected with a thin film metallization step that creates the desired parallel/series combinations to generate the desired voltage output. A thin transparent polyethylene-co-tetrafluoroethylene film is laminated to the surface to protect the cells from the environment and to provide a window for the solar spectrum to penetrate. Figure 2 shows a photo of a small prototype solar fabric the size of a patch or credit card.

Performance

The solar fabric is characterized in the same way that other solar modules are tested. The primary metric for any solar module is the power output at the maximum power point (Pmax) on the current-voltage curve. A high performance I-V curve will have high short circuit current (Isc), high open circuit voltage (Voc), low shunt current, low series resistance, high fill factor (FF) defined as the ratio of Pmax/Isc*Voc, and high efficiency defined as the ratio of Pmax Incident Optical Power. Figure 3 shows a typical P-I-V curve for the solar fabric patch that has an Isc of 64 mA, a Voc of 6.6 V, a Pmax of 337 mW, a FF of 79 percent, a mass of 1.5 g, an efficiency of 13 percent, and a specific power of 225 W/Kg.

The specific power demonstrated here is the highest value for any commercial flexible panel on the market today. However, there are still more straightforward ways to increase the efficiency and reduce the mass to increase the specific power even further.

Next Steps

All of the data discussed to this point is based on solar fabrics utilizing two junction cells. Triple junction cells with efficiencies exceeding 30 percent at one sun, are now readily available for printing to solar fabrics. In addition, the area associated with the streets and avenues between the solar cells represents optical loss and can be reduced relative to the active area of the cells. Finally, the polymeric materials utilized in the prototype

Figure 2

It is reasonable to suggest that even more applications will come to light as thought leaders become more aware of the capabilities of this new material.
IQT Quarterly

Semprius, an IQT portfolio company, designs and manufactures Concentrator Photovoltaic modules for utility grade solar farms and flexible solar fabrics for applications requiring very high specific power. To learn more, visit www.semprius.com.

Samples were chosen because of their availability in the marketplace at low volumes, but thinner, more lightweight materials are available in high volumes. Utilizing the improvements above, solar fabric efficiencies can exceed 20 percent and specific power ratios can exceed 500 W/Kg. In time, solar cell efficiencies will exceed 40 percent at one sun, which will push the specific power ratio even higher.

Finally, it is important to remember that performance is only one aspect of a commercial product. The manufacturing process needs further development to introduce the appropriate process controls, increase yields, and reduce costs. In addition, special coatings can be developed to make the solar fabric stealthy when discreet operations are warranted.

Figure 3 | Typical P-I-V Curve
The IQT Quarterly examines trends and advances in technology. While IQT continues to seek out cutting-edge technologies in the robotics space, several companies in the IQT portfolio are developing solutions with the potential to support this unique industry.

**InView Technology Corporation**
InView Technology Corp. develops innovative computational imaging technology that reduces the cost and improves performance of traditional cameras. The company’s cameras and imagers utilize compressive sensing to capture light outside of the visual range to provide valuable information in optically challenging environments. Operating in ultraviolet, visual, infrared, and terahertz wavebands, InView cameras can process images at great distances despite atmospheric noise. InView Technology Corp. has been an IQT portfolio company since November 2010. [www.inviewcorp.com](http://www.inviewcorp.com)

**MotionDSP**
IQT portfolio company MotionDSP specializes in video image processing software to enhance pre-recorded and live video. The company’s Ikena software utilizes a series of advanced algorithmic filters to stabilize and drastically sharpen blurry, shaky video. Ikena has been used extensively for forensic video analysis, and processing live video feeds in real time from ground and aerial sources, making it easier to identify people and objects captured on film. IQT initially invested in MotionDSP in April 2007. [www.motiondsp.com](http://www.motiondsp.com)

**Pelican Imaging**
Pelican Imaging is focused on creating small, high-performance cameras that address the challenges posed by conventional camera design and small pixels. Their wafer-scale cameras utilize a novel architecture and unique software algorithms for improved performance, including low-light sensitivity, dynamic range, white balance, near focus, anti-shake, and low-power photography. Pelican Imaging is targeting the smartphone market with the goal of supplying high-resolution, ultra-thin cameras at a low cost to manufacturers. Pelican Imaging has been a member of the IQT portfolio since March 2010. [www.pelicanimaging.com](http://www.pelicanimaging.com)

**Infinite Power Solutions**
Infinite Power Solutions (IPS) develops small, thin film energy storage devices for a wide range of applications. The company’s THINERGY™ products offer solid-state rechargeable batteries with the capability to harvest energy from a variety of environmental sources such as solar, thermal, RF, magnetic, and vibration energy. These thin, flexible devices can power wireless sensors, communication devices, and small UAVs, operating efficiently even in extreme temperatures. IPS has been an IQT portfolio company since August 2006. [www.infinitepowersolutions.com](http://www.infinitepowersolutions.com)