FINAL REPORT

CECD/ME SYMPOSIUM ON AUTONOMY

May 15, 2014, 9am-6pm
DeWalt Conference Room
University of Maryland
College Park, MD 20742

Prof. Davinder K. Anand

INTRODUCTORY REMARKS

On behalf of the symposium conveners, who are Prof. Firebaugh, Prof. Short and myself, I want to welcome you to this symposium and thank you for taking the time to come. The topic under consideration is important indeed. Unmanned and autonomous systems are in their infancy today but are going to be powerful and ubiquitous systems in the future in all aspects of our lives.

The purpose of this symposium is threefold. The first is for all of us to learn what each of us is doing now and what we think is the future in autonomy. We want to learn from industry, the government, and our faculty. Secondly, we want to create a continuing platform for discussion and establishing and strengthening working and ongoing relationships. Finally, we want to see if we can identify some niche areas of particular interest to the state of Maryland given its location adjacent to the nation's capital.

Some of you have very targeted presentations, some have overviews, and others more detailed research discussions. All of these are welcome and when combined will give us a kaleidoscopic view of autonomy.

The Honorable John Bohanan was going to be here to welcome you but he has been called by the Speaker of the House and the Governor to attend meetings at the State of Maryland Technology Development Corporation (TEDCO) and the proposed wind farm discussions they are having. John has promised that he will drop by some time during the day as his agenda allows. When he does come, we will interrupt our proceedings and recognize the Honorable Delegate representing District 29B from St. Mary's County.

Again, many thanks for your being here and now let me turn the podium over to my friend and boss Prof. Balachandran, the Chairman of the Mechanical Engineering Department.

Prof. Bala Balachandran

On behalf of the Department of Mechanical Engineering, welcome to the Autonomy Symposium organized by the Center for Energetic Concepts Development. CECD is one of five centers which call the Department their home. Thanks to the leadership of Prof. Davinder Anand, a former Department Chair and the Center Director over the last 15 + years, this center has been a vibrant hub of activity in the Department and Campus.

Given the activities in the different centers of the Department and our history of involvement in robotics, manufacturing, and energy research, it is fitting to have this symposium here today. I am pleased to see participants from industry, government laboratories, and faculty members from different units of the College in this symposium.

A big thanks to Profs. Dave Anand, Millard Firebaugh, and Jim Short for organizing this symposium. Thanks to all of you for being here today.

Look forward to the different talks.

Prof. Millard Firebaugh, RADM (ret.)

Autonomous systems have emerged as a matter of popular interest in the last few years in no small part because of the generally successful and increasingly widespread use by US forces of unmanned aircraft and other types of autonomous systems in warfare. The pace of development of autonomous systems for a variety of functionality seems to be accelerating. Micro and now nano-electronics advances and the accompanying innovations in computers and computer programming are at the core of what is beginning to look like a revolution in the development of autonomous technology, but autonomy is inherently multidisciplinary. Autonomous systems sense and respond to the environment in which the system is operating in order to carry out some task. Accompanying the revolution in the technologies upon which autonomous systems rely, is a revolution in the imagination of technologists and users regarding new, often very sophisticated, applications. The implications of the autonomy revolution, now apparently in its early stages, may be astonishingly profound in their influence on the way we live our lives. Accordingly, UMCP needs to be thinking deeply as to not only the technology of autonomy but also the economics and socialization of autonomy in a future that may be arriving more quickly than one might anticipate.

Capt. Aaron Peters

Capt. Peters mainly spoke about where autonomy fits at the Indian Head Explosive Ordnance Disposal Technology Division (IHEODTD), some autonomy integration efforts, current challenges in deploying autonomy, and how autonomy is likely to be used in the future at IHEODTD. Some of the application areas are: autonomous navigation and manipulation, autonomous mapping, and autonomous tool change-out. Robotic systems called “Mark 1” and “Mark 2” were given as examples of platforms where some autonomy has been added. For these specific platforms, autonomy has mainly been focused on autonomous navigation and situational awareness. It was mentioned that some of the biggest challenges with making these robotic systems more autonomous was lack of access to proprietary technologies and interfaces as well as very high cost of upgrades. Capt. Peters also listed a number of lessons that have been learned so far. One of them is that autonomous capabilities -- or at least requirements specification -- should be added early in the development of a robotic system. It is difficult to add autonomy to legacy systems. Another lesson is that any autonomy that is integrated into EOD robotic systems should be robust enough to handle varied dynamic environments. Some of the predicted future directions include (1) communication of autonomous ground vehicles with air vehicles, enabling extension of operating range, (2) increase in capability of manipulators, and (3) control of robotic systems at a higher level (i.e., give the robot a task rather than a set of specific commands/actions).

Dr. Stuart Young

Dr. Young discussed several efforts at ARL He mentioned that they focus more on basic research and collaborate heavily with universities. Dr. Young showed a few photographs of one of their facilities, which appeared to be a mock-up of an urban environment. He pointed out that one of the main goals is autonomous operation of a collection of collaborating robotic systems in a dynamic, unstructured environment in order to enhance the situational awareness of soldiers. At the higher level, their goal is to transform robotic systems from tools to team members or “bird dogs.” Another goal is to build trust with the operators by providing constant feedback to the operators on what the robot is doing. One of the projects he highlighted was the development of a swarm of miniature quadrotors. Another mentioned project was autonomous navigation while gauging communication capabilities of the UAVs for the purpose of setting operational constraints based on communication capabilities. Some of the other mentioned thrusts were collaborative mapping and sensor fusion, bio-inspired sensors and bio-inspired robotics.

Dr. Susan Hill

Dr. Young and Dr. Hill are both part of the ARL Autonomous Systems Enterprise; therefore, Dr. Hill made some very similar points, though her main focus is on Human-Robot Interaction (HRI). The main goal is to devote fewer human cognitive and physical resources to managing a robot. One of the benefits of this is less workload and greater situational awareness. Some of the autonomy objectives they wish to achieve are: increased situational awareness, tactical reasoning and movement, manipulation of objects (like obstacles) in the physical world, and efficient interaction with operators. Dr. Hill showed an animation depicting some of the capabilities they are trying to develop. In the video, a robot similar to a

Packbot or Talon was shown being deployed by a group of Soldiers in an urban environment. The robot navigated toward a semantically labeled location, i.e., “go to the back of the building”, while avoiding obstacles using tactical reasoning -- looking both ways when crossing a road or moving along a wall. The robot was also shown detecting motion of people, taking video of various people and streaming it to operators. Finally, Dr. Hill emphasized that transparency is an important issue. This involves conveying useful and understandable information to the operator, building trust in the process.

Dr. Bob Bonneau

One of the areas they are working on is complex networks that employ unstructured machine learning, in which they build complex mathematical models of the environment. The goal of the network is to automatically repair or reconfigure itself if communication between a UAV and an operator is failing, while a UAV is flying within the network. This creates a self-configuring network infrastructure, involving both backbone network technologies like fiber optic cable and ad hoc mobile networks. He mentioned that some companies are just starting to deploy these sorts of technologies, but the difference between his group and companies like Google is that his group is looking beyond the 12 month business cycles and short-term ROI. They are looking 10 to 15 years into the future.

Dr. David Han

Dr. Han started out by pointing out some differences between the Air Force and the Navy in the challenges that they are confronted with in operating unmanned systems. His position was that the Navy faces greater challenges than the other Armed Services due to the fact that the communication bandwidth at sea is extremely small and the fact that an unmanned system cannot easily be retrieved and must fend for itself once dropped off. The main objective for the Navy is to transfer dull, dirty, and dangerous jobs from the sailors to the robots. Dr. Han went over what ONR looks for in each of the three funding categories: basic research, applied research, and advanced technology demonstration. Current problems with using unmanned systems include: too many operators needed to control an unmanned vehicle, high operator skill required, and unmanned vehicles tend to be brittle (fail easily). His program is trying to solve these problems. At the basic research level, ONR is focusing on four areas: HRI (includes perceiving intent of adversaries and operators, autonomously distributing workload), perception and intelligent decision making (includes comparing inputs to internal model for detection of sensor flaws), robust distributed collaboration, and intelligent architecture.

Prof. James Short

The DoD Unmanned Systems Integrated Roadmap, FY2013-2038 announces a vision and strategy for the development, production, test, training, operation, and sustainment of unmanned systems technology across DoD. The vision is clear—drones and other unmanned systems are integral to the future operations of the United States Military. The week prior to the symposium, the Center for Strategic and International Studies released a report entitled *Sustaining the U.S. Lead in Unmanned Systems*. CSIS reports that there is no tie between the Roadmap and DoD's Planning, Programming, Budgeting and Execution system. It is PPBE, not the Roadmap, which allocates the funds to create and field military future capabilities.

DoD is consciously taking an unmanned vehicle procurement pause at the end of a decade of war because the military has a surplus on unmanned vehicles. Regrettable is that during the pause DoD is not investing more in the next wave of unmanned technologies. It is the hope of the organizers of this symposium that collaborations of representatives of industry, academia, and DoD such as took place at the symposium will influence the DoD's decision makers to align the PPBE budgeting process with the Unmanned Systems Roadmap and insist that DoD invest in the next wave of unmanned technologies.

Capt. Ronald Harris

Capt. Harris briefly went over several systems built by Lockheed Martin including a high altitude airship that operates at 80,000 feet, a ground vehicle called MULE, and a remotely operated USV that searches for mines. He then went over some objectives of autonomy, which include shifting jobs that are dull, dirty, and dangerous to machines and reducing the number of personnel needed to operate the unmanned vehicles. Capt. Harris also briefly went over the journey of autonomy with the final point being that one of the future thrusts is teams or swarms of unmanned vehicles. The next important point was an example of a squadron of four Predator drones that requires 79 people to manage and operate, with 49% of them performing operator duties. This was meant to emphasize the need to use autonomy in reducing the number of personnel controlling the unmanned systems. While presenting his last slide, Capt. Harris challenged the assertion that there is a reduced emphasis on autonomy within the DoD. His point was that it depends on where you look. His own prediction is that there may be less emphasis on ground-based vehicles, but most likely strong interest in air vehicles due to their potential to exert military force without ground engagements. Capt. Harris then speculated that there are at least three business domains for autonomy: military (scouting, deciding, executing, evaluating), government (transportation, medicine, etc.), and the private sector (mining, undersea rigs, energy).

Dr. Alan Lytle

Dr. Lytle started out by mentioning that there was limited information available from Northrop Grumman for public release. He focused primarily on a set of videos (rather than slides) to show some work being done at Northrop Grumman. The first video provided highlights of the Navy's X-47B Unmanned Combat Air System (UCAS) demonstration program and showed the successful flight operations aboard the aircraft carrier USS Theodore Roosevelt (CVN 71). The Navy's X-47B UCAS team won the prestigious Robert J. Collier Trophy at the U.S. National Aeronautic Association award for this aviation milestone. The second video showed a revolutionary new capability in mine hunting through the use of a mostly tele-operated USV deploying mine detection sensors. Captain Peters pointed out that USVs like this are very valuable to the Navy due to the significant cost reduction associated with using this option instead of air-based solutions.

Dr. William Prins

Dr. Prins first gave some history of ATK and listed some of the areas in which ATK is involved in. These include: aerospace (civilian aerospace, satellites, launch technologies), defense (guided missiles, small arms ammunition), and sporting goods. Dr. Prins also showed a video of one project they did for NASA, where some autonomy was built into an escape pod in order to detach and guide it safely away from a malfunctioning booster rocket. During the Q & A session, Dr. Prins pointed out that they make heavy use of automation in the manufacturing process of some of their components due to the unsustainable labor costs that would result from the use of craftsmen. For some of their mass-produced components, the cost is measured in pennies per unit. In answering another question, he added that the logistics (storage and movement of materiel to point of assembly) is also heavily automated in large part because the materials are so dangerous to handle.

Prof. Satyandra Gupta

Prof. Gupta manages two programs at NSF. One of them is called the Robust Intelligence Core Program within the Division for Information and Intelligent Systems. It investigates issues that range from machine learning to perception, planning, artificial intelligence, and natural language processing. Prof. Gupta focuses mainly on intelligence for robotics. The other program he manages is the National Robotics Initiative, which is a multiagency collaborative effort comprising NSF, NASA, NIH, and USDA. Proposals come to NSF and panels are formed to focus on the interests of individual agencies. Some of the topics of interest to NIH are surgical interventions, assistive technologies, prosthetics, and lab automation. USDA is primarily interested in harvesting and inspection. NASA is mainly interested in robots that could operate on other planets and robots that can assist humans in space missions. NSF is interested in manufacturing, transportation and energy, homeland security, and emergency response. The original goal for NRI was to allow humans to collaborate with robots rather than design robots that can replace humans. NSF budget for NRI is $30 million per year. NASA and USDA invest about $5 million each.

Del. John Bohanan

Del. Bohanan represents Maryland Legislative Election District 29B (St. Mary's County). He mentioned that he just came from a TEDCO award ceremony, so he took the opportunity to briefly describe TEDCO. TEDCO is a relatively small entity that is in charge of boosting economic activity in the State of Maryland by assisting start-ups, helping established Maryland companies, and fostering commercialization of technologies being developed at the universities. He also brought up the work of the Maryland Department of Business and Economic Development (DBED). Del. Bohanan stated that many States expend significant amounts of money at efforts to bring the next big manufacturing plant to their State through organizations like DBED (He implied that this has had mixed results). He went on to suggest that Maryland is taking a hard look at DBED right now to figure out if "it is the right organization for the time that we are in." Del. Bohanan chairs the State of Maryland Appropriations Subcommittee on Education and Economic Development. Education now consumes over half of the State's general fund. Due to the major role education plays in the State budget, he and his colleagues do not have much time to spend on economic development, and as a result DBED has been neglected for a long time. He went on to say that over time the strategy to ramp up the economy in the State of Maryland has shifted from investing in organizations like DBED to investing in higher education. He also gave credit to the U.S. Navy for fueling the Maryland economy, and the local economy of St. Mary's County in particular, by annually putting around $38 billion through the Naval Air Station at Patuxent River (Lockheed Martin receives about $44 billion). He concluded by saying that his goal is now to diversify the activities of the skilled workforce that is resident in Southern Maryland, owing to the Navy's investment. This is where the universities and the development of autonomy come into play.

Prof. Derek Paley

Prof. Paley runs the Collective Dynamics and Controls Lab (collective refers to groups). Their work focuses on air and ocean. He started his talk by showing a video depicting their latest project -- a robotic system that mimics the abilities of a fish to sense flow of water around it and sense its surroundings in general. He also briefly described another fish-related project funded by the NSF that examines the schooling behavior of fish (when they are startled, for instance) while they are in an aligned school versus while they are in an unaligned school. Prof. Paley's group uses flow to guide the school into an aligned formation (fish have a natural tendency to align upstream a current). Prof. Paley and his team have built a robotic fish analog that is capable of performing rudimentary maneuvers, such as orient upstream or move into wake of stationary obstacle, autonomously. Their work creates a tight coupling between perception and behavior with potential for fast response time. More autonomy could then be added on top of these building blocks. For future projects, Prof. Paley wants to investigate fish-inspired propulsion that extends their current work. His idea is to build a flexible robot, with many degrees of freedom, by making use of silicone rubber.

Prof. Inderjit Chopra

Prof. Chopra's work focuses on rotorcraft. He discussed mainly two projects that involve some autonomy. One of those projects seeks to solve problems related to landing a helicopter in a very dusty environment, where visibility quickly becomes very poor. Their solution is to develop an autonomous landing. Another program entails the use of palm-sized air vehicles. These air vehicles comprise both rotary and flapping craft. The goal for this family of craft is to satisfy a variety of requirements like for example endurance, wind tolerance, maneuverability, flying in tight spaces, and hovering. Prof. Chopra and his team successfully built a cyclocopter that has a very high maneuverability and high efficiency. The problem with cyclocopters is that they are extremely unstable, making it difficult for humans to control them. They have solved the control problem by designing and building their own in-house electronics. One of the projects, where they will focus their effort in the future, is an autonomous vehicle for the Mars mission in collaboration with JPL.

Prof. Dana Nau

Prof. Nau works in artificial intelligence and devotes significant effort to a subfield called planning. Prof. Nau and his team primarily conduct research in high level planning, which generally stays above motion planning. Some examples of successful applications of his group's research are: a subsystem within the Mars rover project, sheet metal bending, "City in Your Pocket" phone app, SHOP and SHOP2 software, and computer game AI. One project Prof. Nau mentioned is the Bridge Baron, a special-purpose planner that won the 1997 championship of Computer Bridge. The Bridge Baron carried out planning by generating game trees that corresponded only to known game strategies (a conventional game tree would have 10^{24} leaf nodes). This allowed the software to quickly calculate utility values for the smaller game trees. Another project he was involved in was the development of planning software for a sheet metal bending machine. This project was successful because the problem domain satisfied many of the assumptions of an ideal planning problem: one agent (plan executor), planning is done in advance, world is static and controlled (actions have predictable effects and the plan executor is the only source of change). In a first person shooter type of game, one would normally deal with constant change in a dynamic world by re-planning many times per second. Finally, Prof. Nau pointed out that in the real world, a plan may be partial due to lack of information or constraints on computation time; however, that is acceptable as long as the cost of mistakes is lower than the cost of the planning, the data gathering, and the modeling of the world.

Prof. Gilmer Blankenship

Prof. Blankenship discussed a collection of small projects his students have worked on over the years. The first example is a little ground vehicle with a camera intended to assist people with blindness. The vehicle navigates through a hallway, while reading name plates outside the doors, using the OpenCV computer vision software. Another project was the development of a phone app that tracks a person in GPS-denied areas like buildings. The created tracks can be used to construct a map of the building. The next mentioned project deals with cooperation between multiple agents to solve a puzzle: exiting a room. Though the system is only a simulation for now, it demonstrates the utility of sharing information to accomplish a task. Some of the other small projects that were discussed include a two-wheel Segwaytype of vehicle, a following vehicle, evading vehicles, and racing vehicles. Finally, Prof. Blankenship mentioned that his students built a fairly serious C++-based software framework for working with robots. This library is called Autonomous Systems Library and provides an infrastructure for adding in sensors, actuators, communication devices, and algorithms.

Prof. Nikhil Chopra

Prof. Chopra gave a talk on control of networked semi-autonomous robotic systems. He first went over some challenges in building a humanoid robot that is capable of manipulating objects in its environment. These include the difficulty in building planners for high dimensional robots and the inadequate robot learning ability from past experiences. As a result of these challenges, we must introduce human assistance into the system. And in order to make this human assistance effective, the robotic system should be able to provide extensive information about its environment to the human, ranging from visual to haptic. Prof. Chopra and his team have come up with a framework for integrating human supervision with autonomous operation by employing some autonomous subtask controllers, such as collision avoidance and joint limit avoidance. They are also working on extending this framework to swarm collaboration. In this case, a human operator just gives a swarm -- or a collection of possibly connected robotic components -- a high-level task like moving the center of mass of the swarm to a particular position/orientation and the swarm of robotic components take care of the low-level control. Prof. Chopra brought up the possibility of using the Cloud (Internet servers) to tap the robots into more information and more computational power.

Prof. Nuno Martins

Prof. Martins' presentation was on co-design of software algorithms, hardware, and HRI. One of his first points was that you often cannot design hardware without consideration of the software algorithms that will run on it. The same can be said about the design of software. His talk focused on networked decision systems as one example of such co-design. Networked decision systems are a response to the shift from the classical sense-compute-actuate control system to the increasingly prevalent communication-based model (with communication added to the sense-compute-actuate loop) found in complex robotic systems with many subsystems, acting as agents (decision makers). Some examples of networked decision systems are a pair of aircraft cooperating to avoid a collision and a convoy of vehicles that must coordinate with each other to avoid collisions. This is a difficult problem because in many cases you are trying to optimize certain parameters (e.g., aerodynamic drag for each vehicle in a convoy) or you must adhere to a certain communication structure (e.g., there is a chain of links between the vehicles in a convoy) or you must provide certain guarantees. Prof. Martins briefly mentioned some projects he worked on in this area. One project concerned the development of control software with a communication structure constraint. Another project investigated distributed tracking algorithms. Yet another project focused on research into collaboration and distributed tracking when there are tight constraints on communication, such as a maximum of two or three simultaneous transmissions.

Prof. Don Devoe

Prof. Devoe spoke about MEMS sensors. Due to the commoditization of sensors in recent years, and the widespread availability of good COTs sensors for all kinds of applications, Prof. Devoe has directed some of his research into enhancing existing sensor technology through the use of micro-actuation. The idea is to combine sensors with actuation to improve either accuracy or efficiency or reduce the cost. In the past, if someone wanted to capture high resolution information for a large field of view, one solution is a large set of sensors fusing their data together through software. This created a power hungry and computationally costly system. Prof. Devoe and his team approach this problem by using actuators to constantly reposition a much smaller set of high-resolution, low field of view sensors. Other ways in which actuation can be used in combination with sensors is stabilization of measurements or the use of simple autonomy that is integrated into the sensors. One project Prof. Devoe presented dealt with small-scale motors based on traveling wave ultrasonics. This technology provides advantages such as zero-power positioning (e.g., when you turn the power off, the motor stays in its position). These are also low-weight devices with high efficiency. Prof. Devoe experimented with this particular technology in collaboration with Prof. Bergbreiter.

Prof. Sarah Bergbreiter

The focus of Prof. Bergbreiter's work is the merging of microfabrication with robotics. Her team uses microfabrication to not only build small-scale robots, but also improve the performance of larger robots in sensing and actuation. Among other things, they work on microfabrication with multiple materials (incorporation of silicone), fabrication of tiny actuators, development of legged locomotion (micro-scale), and electro-adhesion. One of Prof. Bergbreiter's goals is to push some of the sensing and control into the hardware, mimicking, for instance, life forms such as cockroaches that navigate a rough terrain, using basic reflexes. Some of the projects she is involved in look at ways of embedding flexible materials into robotic systems. She also directs projects in tactile sensors and all-elastomer electrostatic motors, where conductive particles are added to silicone rubber allowing the composite material to bend in reaction to input voltage. One of the future applications Prof. Bergbreiter wants to investigate is the use of actuators with sensors to enhance the functionality of sensors, akin to a mouse moving its whiskers.

Prof. Jeffrey Herrmann/Prof. Shapour Azarm

Prof. Herrmann and Prof. Azarm presented some preliminary results and ideas for an autonomy-related project they will be collaborating with NAWCAD on. This project will focus on developing risk-based path planning for UAVs. The idea is to find a path to a target that is optimized for multiple objectives. These objectives include things like maximizing the distance from no-fly zones, reducing the flight time, and minimizing the crosswind. The planning software must be able to cope with uncertainty like wind and weather. Another aspect of the project will focus on using Monte Carlo simulations along with the flight characteristics like heading and glide ratio to determine a distribution of possible crash sites.

Dr. Robert Finkelstein

Dr. Finkelstein started his talk by describing a project (funded mainly by DARPA) that sought to build a prototype robotic system called the Energetically Autonomous Tactical Robot (EATR). The concept behind EATR is to have a long-endurance ground vehicle that is capable of extracting energy from its environment, mainly from biomass. This robotic system was designed to use an external combustion engine. The plan was to use a steam engine designed by a company in Florida called Cyclone Power Technologies. As the company's website states, "The Cyclone Engine is a Rankine Cycle heat regenerative external combustion engine, otherwise known as a 'Schoell Cycle' engine. It creates mechanical energy by heating and cooling water in a closed-loop, piston-based engine system." According to his team's calculations, the envisioned engine would allow a stripped down HUMVEE to drive about 100 miles on 150 pounds of vegetation. Dr. Finkelstein and his team carried out a laboratory demonstration for DARPA at the University of Maryland, but unfortunately, funding did not materialize to take the concept to the next level. Dr. Finkelstein spent the second half of his presentation talking about his thoughts and predictions on the impact of autonomous robotics on the future.

Dr. Huan Xu

Substantial research challenges exist in the design and verification of large-scale, complex, distributed sensing, actuation, and logic control systems. Ways to formally and automatically specify requirements, and synthesize reactive control protocols are being demonstrated using an aircraft electric power system as a representative application area. Rapidly improving technology and recent advances in control theory, networked systems, and computer science gives the opportunity to improve our approach to integrated flow of information and cooperative behavior. Where current systems rely on text-based specifications and manual design, new technology advances enable easier, more efficient, and cheaper ways of developing these logic control systems.

Prof. Jaydev Desai and Mr. Chad Kessens

As robots are tasked with increasingly diverse requirements, the grasping and manipulation of unknown objects becomes ever more important. Thus, end effectors should be able to grasp the widest possible range of object shapes and sizes.

In the Robotics, Automation, Manipulation, and Sensing (RAMS) Laboratory, we are working towards the development of a passive grasping technology that can be used to grasp a variety of objects with applications in:

- Rehabilitation robotics for grasping objects during stroke recovery,
- Military such as turning a door knob/opening a door in an urban warfare scenario,
- Underwater robotics,
- Automotive industry for picking and placing large and small automotive parts,
- Agricultural industry for fruit picking,
- Packaging operations, etc.

We are also working towards the development of a robotic hand with compact actuation technology that can be used to actively curl around an unknown object and engage passive grasping through the suction cups.

We have a 2013 U.S. Patent 8,382,174titled: *System, Method, and Apparatus for Suction Gripping.*

Prof. Miao Yu and Dr. Haijun Liu

Toward providing novel acoustic sensors for autonomy, the research at the Sensors and Actuators Laboratory (SAL) is aimed to address the fundamental limitations in conventional sensor technologies. One is the size constraint in sound source localization where the directional cues are proportional to the interaural separation. In nature, the parasitic fly Ormia Ochracea has the remarkable ability, given an eardrum separation of only 520 μm, to pinpoint the 5 kHz chirp of its cricket host. Inspired by the fly, a miniature sensor that has the same size as the fly ear is demonstrated to amplify the interaural phase difference by more than 12 times and achieve a localization accuracy of ±2º, which is equal to the fly's ability. The second limitation to address is the minimal detectable pressure, which is limited by the noise floor of the sensor. A gradient refractive index (GRIN) acoustic metamaterial with alternating layers of air and steel plates is developed to spatially compress the sound wave and as a result amplify the pressure field. We demonstrate a metamaterial enhanced acoustic sensing system that achieves more than 20 dB signal-to-noise enhancement (more than an order of magnitude enhancement in detection limit). With this system, weak acoustic pulse signals overwhelmed by the noise are successfully recovered. The last example addresses the trade-off between the sensor sensitivity and bandwidth by utilizing graphene based nanotechnology. At a layer thickness of a single atom, graphene has a Young's modulus of 1 TPa and can be stretched to as much as 20%. Due to its unique combination of extremely high Young's modulus and extremely thin thickness, graphene fares better than other materials as the diaphragm material. An acoustic sensor with few-layer graphene on the tip of an optical fiber is developed. With an overall diameter less than 150 μm, this sensor has a mechanical sensitivity of 1.2 nm/Pa and a flat frequency response up to 13 kHz.

Prof. Davinder K. Anand

DISCUSSION AND CONCLUDING REMARKS

When we were preparing for this symposium, although we did think of policy and legislation of the kind John Bohanan would be concerned with, we were certainly not thinking of major employment changes and job loss by the millions, an industrial revolution, vast wealth generation, ethics, morality, and rules of war. Yet, these are some of the issues Dr. Finkelstein has touched upon. Suffice it to say, and I do believe that when autonomy has been significantly integrated in our lives, there will be huge changes in our lifestyles. Clearly a broader symposium in Autonomy is in order at another time. This symposium has barely touched the surface of this new and exciting topic and we have limited ourselves to the technical and scientific aspects of the problem. With that said, we will open the last half hour to discussions on any topic you feel is important.

Thank you again and please join us at the wine reception next door.