Robotics

PERSONAL, TECHNOLOGY AND VIEWPOINTS (PART 1 OF 2)

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N.Ed.: Dr. Andrew Goldenberg is the 2016 recipient of the IEEE Canada McNaughton Gold Medal, the highest award given by IEEE Canada.

PREAMBLE

MY CAREER IN ROBOTICS has been marked by "unplanned stages," nonetheless when they are combined they seem to indicate some upper level planning. I doubt this planning was conscious, although I claim I did pursue all steps in accordance with my "best judgement" based on whatever information I had available at any given time, and also based on "gut feeling" and common sense that always served me very well.

I have decided to write about my career with the hope that it will raise, in some ways, a potential interest because of the variety of roles I have played throughout my career. Increasingly, young professionals are told to be prepared for several different areas of employment in their professional life. I have followed a path that included higher degrees education, industry, academia, business and entrepreneurship — unintentionally demonstrating that with hard work, focus and ambition, major career transitions could be extremely rewarding. Seemingly, I have been anticipating the future norm of career changes by several decades.

PERSONAL CAREER STAGES

My professional career is divided into six stages.

FORMATION STAGE

Early on after military service I only partially understood my choices of career; nonetheless I listened, observed and received clues from various sources. It ended up with a great choice of profession: engineering — a perpetually challenging discipline — and electronics, which with the explosion of sensor and microprocessor technology has impacted every facet of engineering. These choices were supported by selecting well-known academic

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One issue that has been pre-occupying me for a long time has been the relationship between academia and industry. I have read many reports in various media addressing the matter, but I have never found sufficient insight nor adherence to my views, until I read an article published in the *IEEE Robotics & Automation Magazine*, Sept. 2016 issue, "Robotics Academia and Industry: We Need to Talk!." The article is authored by Professor Erwin Prassler from Hochschule Bonn-Rhein-Sieg, Germany. He addresses, in part, the long-standing need for greater industry participation in university research. I found the article very interesting, and his assessment of the divide between the two communities by-and-large in agreement with my own.

In my experience, the issues raised in the article apply broadly to most industrialized countries. In this piece, I include many of the points made by Prof. Prassler, adding to them my own observations and beliefs. Whilst he wrote as an academic, I am largely claiming to present the industry perspective.

Why should university research community attract industry? Because:

(a) it is the major reason for its existence in terms of its role in education, training, and use of research results

(b) focusing on research without solving operational problems of interest to industry leads to practical irrelevancy

(c) by-and-large, industry needs the research community — especially in the context of modern robotics: logistics, autonomous mobility, human-machine interaction, reasoning, and machine learning

(d) ongoing dialogue between the two communities builds understanding of their divergent scopes and objectives: Research — publish or perish; Industry — economic relevancy

What kind of industry the research community should aim to attract?

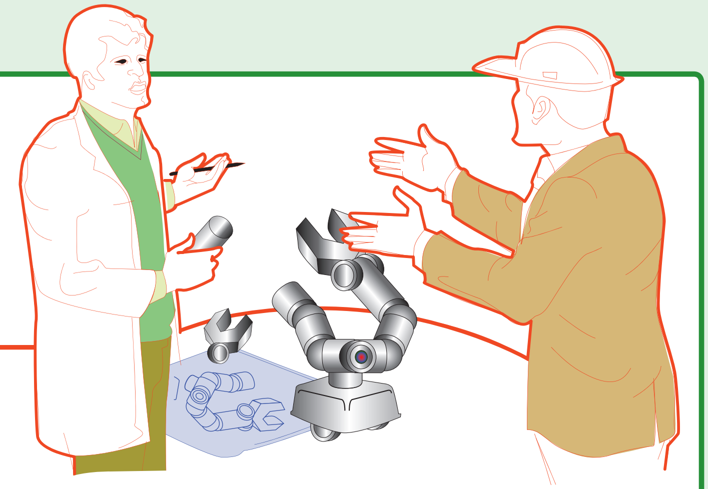
(a) any industry that uses robotics

(b) start-ups in robotics

What makes robotics research attractive to industry?

(a) industry does not perform basic research

Why University Robotics Researchers Need to Reach Out to Industry



(b) industry needs to address advanced topics impacting future product developments
(c) training and advanced education
(d) robotics challenges
(e) publishing survey articles

Origins of academia-industry divide

(a) the control systems research community was the first to address robotics research in late '70s
(b) electromechanical design of robotics was not addressed by the early university research community concerned with robotics – it became the realm of industry. In the '90s the research community became interested, however.
(c) Computer Numerical Control was the first to address robotics as an industry
(d) the computer research community was attracted to knowledge-base and early AI as a bridge to robotics in the '80s
(e) while current university research meets Technology Readiness Level (TRL) 3-4; industry finds it useful only at TRL 7-8
(f) industry does not approach the research community because it sees it as irrelevant to immediate issues
(g) no strong evidence of operational links between university research and industry on issues of immediate concern
(h) industry prefers to perform critical research internally (an IP matter)
(i) embodiment of modern robotics technology requires intensive applied research
(j) university research is primarily dependent on public or institutional funding

Suggested paths to rapprochement between university robotics research and industry

(a) industry addresses development of products
(b) research community addresses basic research
(c) both should aim to generate core technology to be embedded in products
(d) product development and research to be performed simultaneously

Industry is best served by creating products that have a market value, as opposed to laboratory exploration that is the undertaking of basic research. Where academia undertakes applied-oriented research, it could be channeled towards "core technology" that is the foundation of any product. Thus, product development and research would both contribute to the development of the core technology embedded in the products. Core technology, expressed through patents, trademarks, technical secrets and know-how would be valued by the market through its perceived efficacy in creating new products. This market value is further raised by the perceived market impact and penetration of the new products. In this manner, the research becomes relevant to creation of products that in turn may provide sustainment to the research efforts and cover their costs.

Academic and research-oriented institutions focus almost unilaterally on the development of basic technology. They are guided by perceived future market needs, competition between research institutions expressed by the publications and citations of each, and shear curiosity of research staff. These related undertakings are usually not linked directly to product development as done by industry. This leads to excessive generation of basic technology that may — or may not — be useful. Granted though, it may be ahead of the state-of-the-art, sometimes by a decade or more; therefore, one cannot fully assess the impact of generating new basic and core technology.

The fact is that core technology that is directly related to market-driven products is rarely addressed outside those businesses whose main undertaking is to develop the products in the first place. The university-based research could be a significant contributor to the product development if it would allow targeted research to dominate, as opposed to total disengagement from immediate use that loads heavily on the taxpayer money.

ROBOTICS AS AN INDUSTRY

If we look historically at the computer and robotics industries we would note that the latter is older. This may be a surprise if one considers the stage of existence of the computer industry. It is mature and already in its fourth or fifth global business life cycle. The names of Microsoft, Dell, HP, and many others are well known. Why is the robotics industry still in diapers? The main reason is that it evolved as a novel academic exercise instead of being undertaken fully by the business community. Nonetheless, nowadays there are well known names in the robotics industry

> "The primary aim should be to make the robotics industry create jobs for the masses, and not just for those with a Ph.D. Too often unsustainable businesses are created, conceived as high-end "advanced" projects but lacking a fundamental business basis of growth that could lead to job creation."

such as Fanuc, Kuka, Adept, and many more suppliers of subsystems and components. However, as an industry, it still represents a very small number of employees globally, when compared with the computer industry, and is still repeatedly referenced and viewed as an "emerging technology," although the field is more than 40 years old.

It is time to leave out the "wow" of futuristic applications featured in YouTube videos, and get serious with the maturity of the robotics field as a current employment opportunity.

The primary aim should be to make the robotics industry create jobs for the masses, and not just for those with a Ph.D. Robotics should benefit the society at large, instead of the few and far between often supported by ill-informed funding decisions. This applies to both private-sector investments that do not reflect market needs and its capacity to adopt the new technology, as well as government funding that seeks to demonstrate forward-looking economic policies to a public largely ignorant on matters of technology and its impact on the welfare of the society. In either case, too often unsustainable businesses are created, conceived as "advanced" projects but lacking the fundamentals of business growth that could lead to job creation.

ROBOTICS START-UPS

To grow a technology business there is a need to develop a business plan based on a unique business model, as opposed to relying solely on the uniqueness or advanced nature of the proposed technology. Good business models succeed in so far as competing at an advantage, whereas good technologies without a suitable business model do not. This issue relates primarily to start-ups; governments and media focus on the rate of start-up formation as a measure of success. They ignore growth and sustainability in relation to the investment made.

Capturing a novel and unique business model has been my primary pre-occupation throughout my entire business journey. It has proven to be successful. I recommend to not adopt a known or existing business model simply because it is used by others. Devise the unique model that suits you and your technology. ■

Personal Robots

HOST AND RECEPTIONIST ROBOT

The robot for service in public areas. It provides a mobile kiosk to dispense information upon request through touch-screen interface, guidance through Q&A in public spaces, source of local maps, and link to customer relations personnel. The robot can be used in more formal gatherings such as conferences and conventions, sports events, train and bus stations, and airports.

It includes interactive means for two-way interaction with the public in a wide range of venues. It can move autonomously or can be controlled remotely.

The main functionalities and applications are:

- Mobile navigation in public spaces
- Remote viewing, inspection of environments, transfer of images
- Auto docking and power charging with operation of more than 6 hours
- Automatic detection of obstacles and automatic stop for safety
- Local touch-screen display
- Inter-person voice communication including expressions of emotions
- Reception services
- Guidance in public spaces
- Payment outlets
- Advertising and promotion services
- Educational service

HOME ASSISTANT ROBOT

The robot is a mobile device for active support of humans mainly in domestic environments. It incorporates the Mobile Platform and a pair of arms mounted on a vertical trunk attached to the platform. It can be controlled through voice, gesture and display of emotional interaction. The robot can be programmed for specific premises and tasks to help around the house. The robot could help seniors and disabled persons to stand up from the bed and chair. This help could be provided by remote control from a service center. The robot could also provide some functions around the kitchen. The robot could operate with one or two arms.

Working and serving a human interactively raises safety issues. In this context, the arms are back-drivable (compliant joints) to provide a diminishing force of interaction when unwanted contact between robot and human occurs. The robot APM can be mounted on various mobile platforms.

The main functionalities and applications are:

- Mobile navigation in private premises
- Remote viewing, inspection of surroundings, and transfer of images
- Auto docking and power charging station with operation of more than 6 hours
- Automatic detection of obstacles and automatic stop for safety
- Fetch-and-carry tasks such as serving a drink
- Delivery of light items to user
- Provide help to a person to stand up
- Home cleaning and simple operation of appliances
- Door opening and closing
- Doing laundry such as using a washing machine
- Alarm and assist in case of emergency such as in the case of a fall
- Support to do remote control of some personal health measurements
- Entertainment and communication

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institutions for learning: Technion in Israel for 1st and 2nd degree and University of Toronto for the 3rd degree. It worked very well for me because I spotted the right trends.

As an undergraduate, I was a so-and-so student until the 3rd year when I met a better scholar than me from the Faculty of Architecture of the same school (Technion) — my wife of over 47 years. By the 2nd half of the 3rd year I became a studious person, hungry for professional and general knowledge and looking forward to challenges; this continues unabated to date.

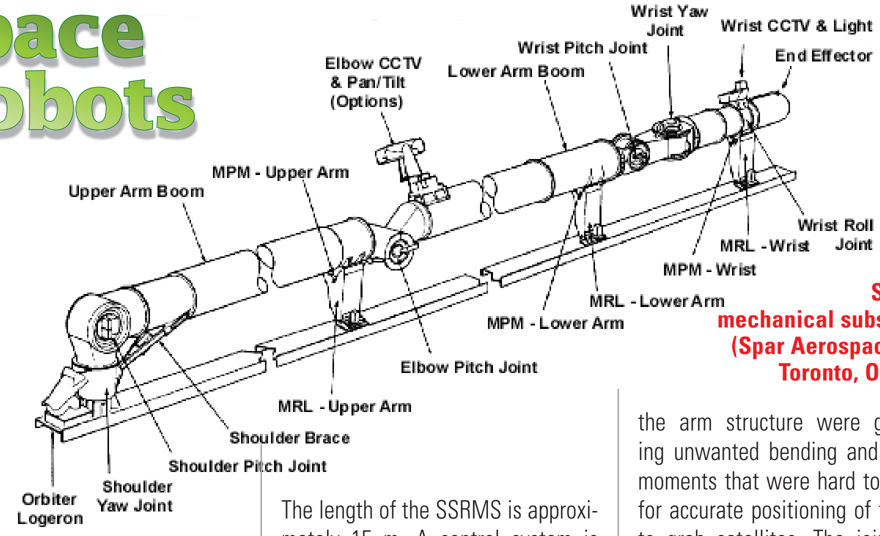
All and all, I have had great undergraduate studies, exceptional graduate studies supervision and great inspiration from selected models — professionals who were unaware that I was studying them, leading to extremely good preparation professionally, mentally and strong habits of working intensively and passionately.

INDUSTRY STAGE

When I finished my PhD at Toronto in 1975 I tried to land a postdoctoral position in Canada; there were not many opportunities available back then that were suitable for me. However, I was extremely lucky to be hired in July 1975 by SPAR Aerospace Ltd. of Toronto to work on what was then called Space Shuttle Remote Manipulator System — SSRMS and later renamed Canadarm. I started working on the control system of the SSRMS joint. Later I worked on the whole of SSRMS kinematics, dynamics and its 99-DOF simulation model, as well as on other space robotics and various satellite projects.

The SSRMS project completely shaped my professional future: it was unique, ahead of the times, very challenging and outrageously interesting. A totally captivating endeavour. It was the period of growing up and maturing professionally (and personally with a pair of identical twin daughters) to eventually realize that knowledge is never complete, and learning is an endless job. This applies to me today as it did then.

Space Robots



SSRMS mechanical subsystem (Spar Aerospace Ltd., Toronto, Ontario)

SPACE SHUTTLE REMOTE MANIPULATOR SYSTEM (SSRMS)

The Space Shuttle Remote Manipulator System (SSRMS) or "Canadarm" was a joint venture between the governments of the United States and Canada to supply the NASA Space Shuttle program with a robotic arm for the deployment/retrieval of space hardware from the payload bay of the orbiter.

A schematic view of the SSRMS is shown at top. It is a robotic arm consisting of a shoulder, elbow and wrist separated by an upper and lower arm boom giving it a total of six DOFs (shoulder pitch and yaw, elbow pitch, wrist pitch, yaw and roll). At a total weight of approximately 431 kg, the SSRMS is capable of maneuvering payloads of up to 14,515 kg at a rate of 0.06 m/sec with a maximum contingency operation payload weight of 265,810 kg. Under unloaded conditions the SSRMS can achieve a maximum translational rate of 0.6 m/sec. However, the SSRMS is incapable of supporting its own weight on earth. It must be supported by specialized ground handling equipment during its testing and packaging for shipment.

Although the SSRMS can handle very heavy payloads, movement of the tip is very accurately controlled, allowing precise handling of delicate payloads.

The length of the SSRMS is approximately 15 m. A control system is used to deploy payloads in automatic mode to a positional accuracy of +/- 2.0 in and +/- 1.0 degree of a pre-programmed target point and orientation at the afore-mentioned rates and load conditions. The SSRMS may also be operated manually (remote control) by the

Photo: NASA

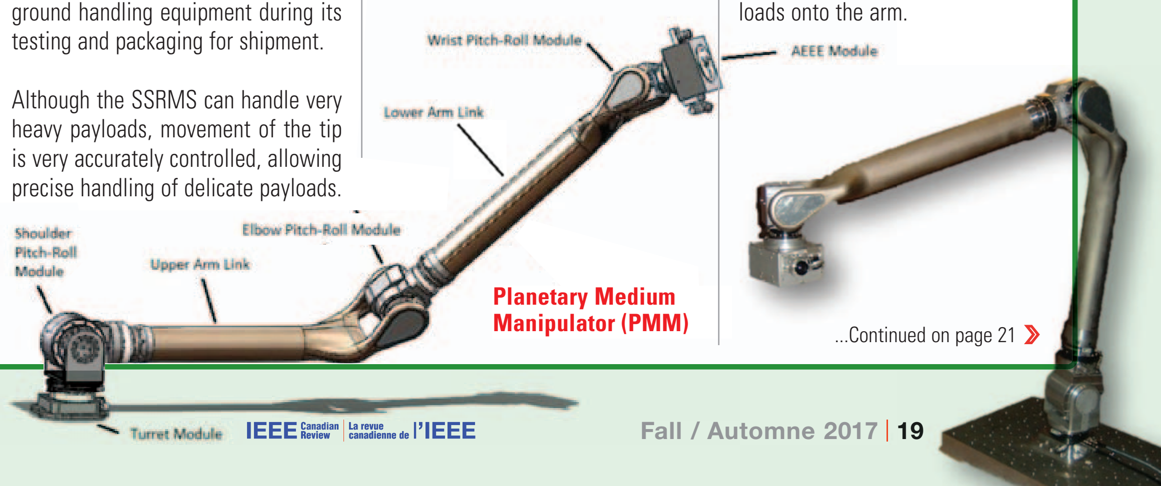
astronauts to the same accuracy with the use of hand controllers and closed circuit televisions (CCTV) mounted on the manipulator arm. The SSRMS was designed to have a life of 10 years or 100 missions.

Analytically, the major challenge in the development of the SSRMS was the structural flexibility of the mechanical system generated by the limitations of SSRMS weight. On the ground the arm had to be supported with braces. In the weightless of space, its own mass was no issue, but the light materials that made the arm structure were generating unwanted bending and torsion moments that were hard to control for accurate positioning of the arm to grab satellites. The joints and the boom were very flexible; the system had 99 DOFs, making the control system design of the joint and of the arm a major challenge that has not been completely solved even to date.

ADVANCED ROBOT ARMS: PLANETARY MEDIUM MANIPULATOR

This robot was developed to advance the state-of-the-art of manipulators for planetary exploration and to perform simulated Moon and Mars missions on Earth. It is made up of eight modules: Turret, Shoulder, Upper Arm, Elbow, Lower Arm, Wrist, Automatic End Effector Exchanger (AEEE) and Controller. The turret provides azimuth motion, while the shoulder, elbow and wrist each provide pitch and roll.

The system operates under remote control commands, as well as autonomously through a scripting interface. The autonomous motion is achieved using advanced methods of visual servo, force, impedance, and adaptive control. The AEEE interface is used to autonomously load tools and other payloads onto the arm.



Planetary Medium Manipulator (PMM)

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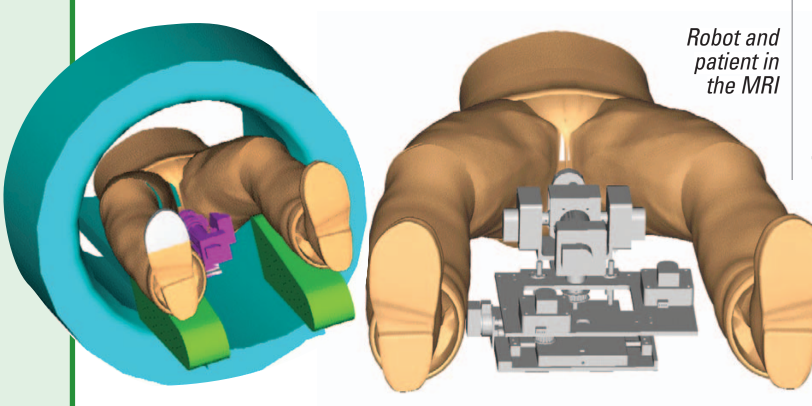
Medical Robots

Medical Robots technology is offered through a range of products. Surgical robots have been developed or are under development for the following therapies: **(i)** Minimally invasive prostate surgery in closed-bore MRI, **(ii)** Minimally invasive general surgery in closed-bore MRI. The robots are modular and re-configurable to allow mounting and fitting into the MRI environment. The robots are semi-autonomous. They are remotely controlled when operating in the human body through MRI and PC-based images. The robots are endowed with advanced Operator Control Units allowing complete control of the interventions. The robots can be adapted to other surgical procedures and organs by exchanging therapy-focused modular subsystems of the robot.

MRI-GUIDED ROBOT-ASSISTED IN-BORE PROSTATE SURGERY



Robot and patient in the MRI

Prostate cancer is the most common cause of cancer in men and the second-most common cause of mortality due to cancer. Publicly available information indicates that more than 230,000 men are diagnosed each year in North America. A conservative estimate of the prevalence of prostate cancer in North American males in the age range of 55 to 69 is 7,500,000 men.

The traditional curative treatments of this disease include radical surgery and external or interstitial radiation therapy. These are reasonably effective for localized cancer, but are associated with significant quality of life penalties. These may include incontinence, impotence, bowel dysfunction, and prolonged recovery. The cause of these problems is not removal of the prostate but damage to surrounding tissue and nerves.

While most believe that prostate cancer is a multi-focal disease, recent evidence supports the notion of a dominant focus that is the largest of intra-prostatic cancer sites and the major source of extra-prostatic spread (90%). Recent improvements in imaging of tissue by magnetic resonance scanning have allowed for the visualization of these sites.

Image-guided focal ablation of the dominant focus in selected men with low to low-intermediate risk cancer can control spread of the cancer from the prostate in most men and render it a chronic disease that is largely devoid of side effects. This paradigm treatment shift is not dissimilar to treatment of colonic polyps by colonoscopy as opposed to colectomy or lumpectomy for localized breast cancer instead of mastectomy.

The ideal implementation of this concept is with a minimally invasive robot-assisted MRI-guided focal ablation system. The procedure is performed in closed-bore MRI that is considered superior to other techniques of image-guided interventions (open-bore MRI, Ultrasound, Computerized Tomography (CT) scan). The procedure uniquely integrates direct cancer imaging, real time precision computer-aided navigation of the tool to the target, optimal energy distribution into the target, real time imaging of tissue destruction using MR thermography for visual confirmation of target destruction.

The robot could be used with different surgical tools to perform a range of prostatic interventions:

- Ablation - thermal lesions resulting in cell death without untoward patient effects
- Brachytherapy - insertion of radioactive seeds in the gland
- Biopsy – extraction of tissue samples from the gland based on established protocols

The image-guided surgical interventions in closed-bore MRI may be performed using either:

- a remotely-controlled surgical robot tool; or
- a manually-controlled instrumented surgical tool

The surgical tool is identical in both approaches. It is carried by either the surgical robot tool or by the instrumented tool. The procedures are image-guided.

One major issue is that the surgical tools and carriers must be MRI-compatible; that is, the robot or instrumented tool and the MRI would not affect each other (the imaging process and carrier operation, respectively). The technology also includes a methodology of evaluating the therapy (ablation) by real-time MRI scanning during and post-intervention.

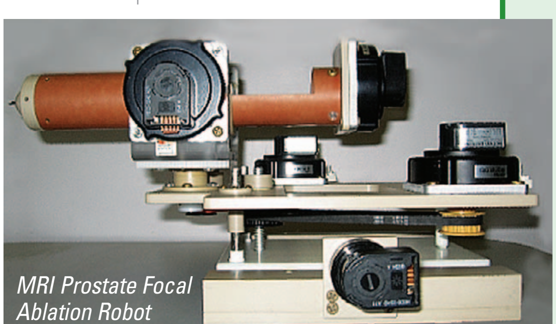
The new technology provides high added value to the medical practice as it would impact on both precision of surgical procedures and reduction of side effects that may appear post-interventional and affect the quality of life.

The robotic platform includes: (i) a six-joint robot; (ii) robot-based trocar for mounting surgical tools; (iii) hand controller for navigating the surgical tool by remote control; (iv) robot controller; (v) a laptop-based user interface for robot control and image display; (vi) laser dispenser, power, and control; (vii) MRI monitoring station (including MR Temperature mapping). The robot system could be adapted for operation in 1.5T - 3T MRI scanners. The robot is functional simultaneously while the scanner is operating without affecting the images or the robot operation.

During surgical procedures, the patient lies on the MRI roll-in table with leg supports attached to the table (shown schematically). The robot is mounted & secured onto the table and between patient's legs. The robot controller is at a distance from the scanner, connected to the robot, and to the Laptop that is in the adjacent control room. The surgeon will remotely manipulate the tools based on MRI and laptop-based images using a hand controller (joystick) or manually. Control of surgical tool penetration is based on visual feedback provided by MR imaging. The image allows the user to identify the tool tip location relative to the target, and perform suitable adjustments of the tool path to reach the target. When the tool is at the target, the laser is turned on, and ablation of tissue is performed. MR thermography allows for real time imaging of tissue destruction. After the ablation process is completed, the scanner provides images of the heated and coagulated volumes of tissue.

The technological features of one such robot are:

- Modular Design: Surgical tool support (trocar) allows for a variety of tools to be used
- MRI-compatible
- Rugged and compact design
- Bio-compatible
- Safe and efficient in the MR environment



MRI Prostate Focal Ablation Robot

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ACADEMIC STAGE

I was very lucky to be called to serve and be hired by the University of Toronto in 1981 on contract as a Research Professor, and later in 1982 as full-time tenure-track Professor in the Department of Mechanical Engineering. The departmental chairman, Dr. Ron Venter, was critical to my quick and successful integration at U of T and early successes.

I became infatuated with robotics: publications galore, very large number of graduate students, activities in professional societies, large research funding, editor of journals, conferences, presentations, speeches, etc.; high international recognition; accolades at right and left including three medals, the last being the IEEE McNaughton, and fellowships in several professional societies internationally, US and nationally.

In fact, I was the founder of the field of Robotics at the University of Toronto where I have been since 1982. I have supervised the largest number to date of graduate students in the Faculty of Applied Science and Engineering (46 PhD and 64 MASc), and have an exceptional publication record with more than 7,500 citations (128 archival journal papers, 294 papers in major conferences, 15 book chapters and 75 patents granted and applied). Though now and since 2011 I am a Professor Emeritus, I still maintain a reasonable load of graduate students and research.

Over the years, I was asked and accepted to be an editor of the archival international journal *IEEE Transactions on Robotics and Automation* from 1986-1994, and I am still a member of the editorial boards of *Robotica*, *Robotics in Japan*, *Journal of Robotics*, *Robotics Journal*, *Scientific World Journal*, *Industrial Engineering and Management Journal*, *SOJ Robotics and Automation* and *International Journal of Automation and Computing*.

From the early work as an academic I needed to show that I can build systems and see how they really work in practice. This prevailed, but it was concurrent with high-end academic work, leading to setting up at the University a commercial undertaking

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Space Robots ...continued from page 19 »

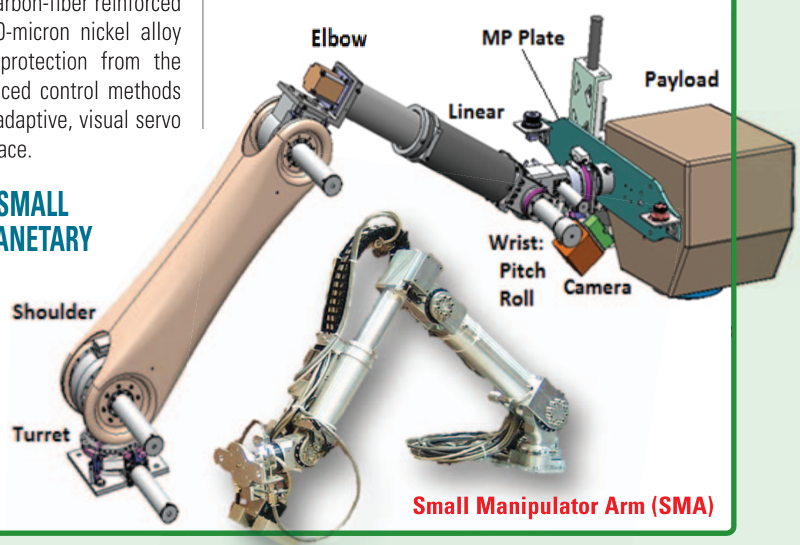
The robot can be used effectively in security and defense applications while mounted on mobile platforms, as well as in manufacturing, robotic-based custom automation, and for research. The robot is 2.3 m long with DOF. It can be used in aerospace applications where light weight is a key factor, security and defence where high accuracy and dexterity is a key requirement, as a test bed for R & D in advanced control methods with open software architecture, visual servo applications of guided tool operations and tool exchanging, and testing in environments with harsh Electromagnetic Compatibility (EMC), temperature and humidity requirements. It can be used indoor and outdoor.

The design is modular consisting of one single-joint and three two-joint modules, links and AEEE. The joints are compliant (back-drivable). Light-weight and high-stiffness arm links made of carbon-fiber reinforced plastic (CFRP) are coated in a 50-micron nickel alloy layer. Internal cabling provides protection from the environment and snagging. Advanced control methods that are used include impedance, adaptive, visual servo control and control in Cartesian-space.

ADVANCED ROBOTS ARMS: SMALL MANIPULATOR ARM FOR PLANETARY EXPLORATION

The Small Manipulator Arm was also developed to advance the state-of-the-art in manipulators for planetary exploration and to perform simulated Moon and Mars missions on Earth. It is a light-weight, high payload-to-weight ratio manipulator with advanced control systems including force control, visual servo control, and open software architecture. The arm has six joints, links, payload interface, electronics (drivers and controller), harness, user interface software, and operator control unit. The arm can be operated in remote control and closed loop modes. It can be used effectively in security and defence applications while mounted on mobile platforms, as well as in manufacturing, robotic-based custom automation, and research. The arm complies with military standard (MIL-STD-461 Rev E) on EMC and Electromagnetic Interference (EMI) requirements, and with space-quality requirements on vibration and shock resistance.

The arm has a high payload-to-weight ratio of 1:1.1, high repeatability and accuracy at full extension, modular two-joint wrist with tilt and roll motion, and a payload interface module for multiple payloads.

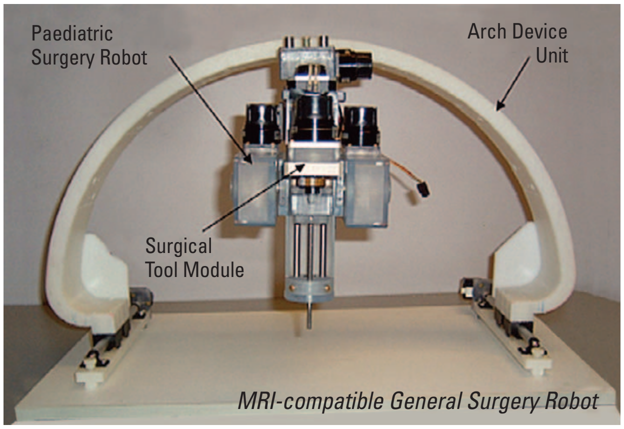


Small Manipulator Arm (SMA)

Medical Robots ...continued from page 20 »

GENERAL SURGERY ROBOT IN MRI

MRI-Compatible General Surgery Robot including its auxiliary technology (surgical tool, control station and arch-base device) is a new surgical robot prototype for MRI-guided bone biopsy and general surgery. The robot is modular, re-configurable and fits into the MRI, mounted on a MRI-bore shaped arch. The re-configurability provides a means of finding the best possible configuration for specific bone biopsy and other surgical interventions. The robot with various surgical tool modules can operate under remote control as well as autonomously. Haptics technology can be used to provide the sensing of drilling force in bone biopsy interventions. Embedded Control Software and Graphical User Interfaces are part of the robot system. Software for visualization and navigation is currently being developed.



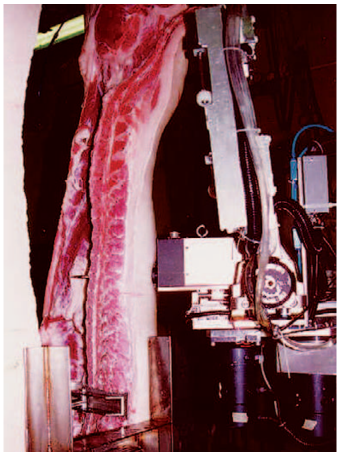
MRI-compatible General Surgery Robot

The main features of the medical robot are modularity of robot and surgical tool, MRI-compatibility, visualization and navigation software for interaction with MR images, and easy attachment/detachment of the surgical tool module for sterilization. An arch device unit compact enough in size to fit in the limited space of 3-T close-bore MRI is also available.

Custom Robots

ROBOT SYSTEM FOR MEAT GRADING

In commercial abattoirs, meat grading is routinely performed to establish the thickness of fat. The grading is performed at a federally-legislated point done in one stroke, at a certain speed, and the needle must be inserted perpendicular to the surface of the meat. In the case of hogs that is at 7 cm from the spine between the third and fourth rib below the neck. When it arrives at the grading station, the carcass is already split along the spine from the tail down about half way. The operator inserts his arm between the two parts of the carcass (the carcass back is facing the operator), finds the third rib, and presses his hand against the third and fourth rib while he inserts the needle. Clearly, experience helps the operator finding the ribs, insert the needle between them, maintain the needle orthogonal to the surface, maintain the speed of insertion, and perform the insertion in one stroke. The equipment is connected to a PC, and it registers the carcass number and the grade automatically.



Meat Grading Robot, Sensing, and Probing Subsystems

Meat Grading Clamping Subsystem

on the back of the carcass. The grading is performed with widely used electronic equipment that measures the thickness. The equipment has a long needle that gets inserted manually by the grader. The equipment measures the impedance of the tissue, and the differentiation between the impedance of the fat and that of the meat generates a reading of the thickness. The grading device, operated by a qualified grader, must be inserted in every single carcass. In the abattoir, the carcass is transported attached to an overhead conveyor. The operator must perform the task while the conveyor is moving, at a rate of maximum 700-800 carcasses per hour shifts in large abattoirs.

This work is performed along the cutting line, as one of the several steps of preparing the meat for packaging. The work is tedious; the environment is hardened by odors, and generally leads to serious fatigue. The operator works continuously only 20 minutes at a time, and rests for the next 20 minutes. Thus, two operators are working in every eight-hour shift. Large abattoirs have two or even three shifts. The fatigue of the operator leads to inconsistent grading. The insertion of the needle must be

The operation described above measures only the thickness of fat. The meat processing industry has been asked to perform additional measurements indicating the quality of the meat. There are developments currently underway to develop measurement devices for all sorts of meat properties. It is also desirable to effect grading in a non-invasive way. This would preserve the integrity of the carcass surface.

The operator fatigue, inconsistency in grading, the need to perform additional measurements, provision for both invasive or non-invasive grading, and the high cost of grading operations have led to considerations of robotic-based automation.

A system for grading hogs was developed in collaboration with the robot developers and pork meat processors. The approach and methodology is applicable to the "red meat" industry as well.

The robot replaces the grader in the repetitive and tedious manual task of grading pork carcasses. Automatic grading can be performed for fat/lean thickness, as well as PSE (paleness, softness and exudativeness) characteristics, and marbling content of a fresh pork carcass.

Automatic grading can be performed: (i) invasively, by the insertion of a grading probe, at a designated spot identified using ultrasound technology; (ii) non-invasively, using ultrasound and infrared technology; and (iii) as a combination of both. Manual fat/lean thickness grading is representative of invasive grading. Non-invasive grading ensures that no cross contamination occurs.

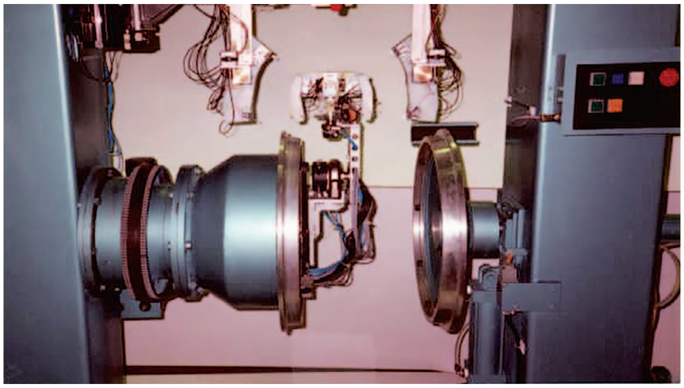
The robot system comprises three sub-systems: Robotic Subsystem, Sensing and Probing Subsystem and Clamping Subsystem. The Robotic Subsystem carries the Sensing and Probing Subsystem which scans the pork carcass, as the carcass is moving along the conveyor line to: (i) locate the designated spot for probing (invasive or non-invasive); and (ii) perform the grading. The Clamping Subsystem automatically clamps the pork carcass as it enters the grading station and presents the carcass at a constant position and orientation during the grading operation performed by the Robotic and Probing Subsystems. The Sensor Probing Subsystem uses a dual-echo ultrasonic technology to detect the probing site and perform the probing.

ROBOT SYSTEM FOR TIRE CASING ANALYSIS

Truck tires wear-and-tear generates a need for replacing them as often as needed. The industry of used tire re-treading is growing, due to environmental concerns. Tire re-treading is a growing business that requires effective detection of used tires that are candidates for re-treading.

An automatic robot-based tire casing analyzer has been developed. It detects defects and wear. It marks the locations of defects, and it provides a report on the state of the tire. The operator then decides if the tire could be re-treaded. For many years, the tire industry has been searching for a nondestructive, simple way to inspect tires and tire casings for flaws. Good casings are presently being discarded and disposed of in landfill sites, causing a detrimental effect on the environment. Or, tires are often prepared for re-treading only to discover that the casing has major irreparable flaws. The new technology eliminates these problems resulting in significant economic benefits. The technology is based on an intelligent controller that uses two robotic systems and carries 28 ultrasonic sensors. The controller provides autonomous positioning and guidance of the sensors, which are delivered into the tested tire by a very compact foldable robot. The sensors manifold conforms to the interior shape of the tested tire. Based on the ultrasonic signal, the sensors detect and evaluate defects in the tire. An intelligent algorithm has been developed to evaluate defects, classify them according to size, shape, etc., and graphically zoom in on a detected defect to be displayed on a computer screen.

The robotic arms are performing the ultrasonic inspection from within the cavity of the tire (carrying the emitters) and over the external surface (carrying the receivers). Loading and unloading of tires is done automatically by the operator using a lifting device.



View of internal and external robot arms carrying ultrasonic sensors

General view of the tire grading system

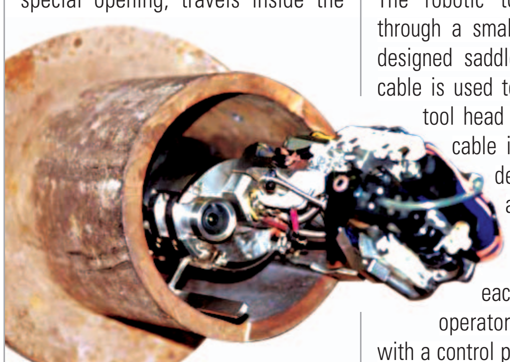
After loading, the unit starts operating by pressing a set of disks onto the sides of the tire to enclose its inner cavity. Then a foldable robot arm that was stowed inside one of the disks gets deployed internally. The robot arm carries a manifold of ultrasonic sensors that have three segments. The segments get deployed in such a way that the center segment faces the inner side of the tire tread, and the two other face the inner sides of the tire. The manifold positions itself at a suitable distance from the internal surface of the tire to enable ultrasonic waves to penetrate and reach the receivers that are connected on an external manifold mounted on the other robot arm external to the tire. Emitters and receivers are automatically aligned for maximum efficiency. The operation of the ultrasonic sensors, including the positioning and alignment is fully automatic.

After both the emitters and receivers were positioned accurately, the tire starts rotating at a pre-determined speed to perform the inspection.

ROBOT FOR INTERNAL OPERATIONS IN UNDERGROUND GAS PIPES

Underground cast iron gas pipes are made from 12′ long sections connected by bell-and-spigot joints. A joint is generally filled with jute packing and sealed with lead. The joint can develop leaks over time and must be repaired. One of the most frequent repair procedures is to inject an anaerobic sealant into the jute packing. This procedure requires a 4′ x 6′ excavation at each joint to allow the utility to reach the pipe (in the north-east US and Canada the pipes are 8′ deep in the ground), drill a hole through the bell into the jute and inject a measured quantity of anaerobic sealant. Such a process is hazardous, laborious and costly, and it interferes with transportation and pedestrians in urban areas.

To alleviate the above problems a novel technique was developed to perform cast iron bell and spigot joint sealing from inside the pipe using a remotely controlled robot. The robot is launched into the pipe through a special opening, travels inside the pipe until a desired joint is reached, and drills a hole into the joint spigot at the highest point. Then anaerobic sealant is injected into the jute packing to re-seal the joint. This approach replicates the repair procedure currently done externally. The sealant flows under gravity and saturates the jute. The operation is done while the main is kept in service.



View of the gas pipe robot end-effector

The internal sealing system can seal several joints from a single excavation while keeping the main in service. The system has been designed for 6″ (15 cm) diameter pipes. It can be inserted into the main up to 150′ (over 45 meters) in each direction from the entry point. Up to 24 joints can therefore be sealed from a single excavation. Adaptation of the concept to larger pipe diameters (up to 36″) has also been performed using a different methodology of moving inside the pipe.

The joint sealing system consists of a small robotic working head equipped with a video camera for search and joint identification, an umbilical cable, cable insertion unit, system storage reel with the tool control components, and an operator's station that includes a control panel and video monitor. In operation, the robot head is inserted into the main through a small tap, and pushed along the pipe by its motorized umbilical cable. The operator visually locates the desired joint, and positions the robot at the joint. The robot head is then raised into drilling position, and a small hole is drilled through the spigot into the joint cavity. Then, the sealant head is rotated into position, and a measured amount of sealant is injected into the joint. The head is retrieved, and the unit is then moved to the next joint.

The robotic tool head is inserted through a small tap using a custom-designed saddle. Semi-rigid umbilical cable is used to push and control the tool head position. The umbilical cable is stored on a custom-designed reel. A miniature video camera mounted on the tool head is used to locate each joint for sealing. The operator's station is provided with a control panel and video monitor, allowing remote control of the tool head for drilling and sealant injection. ■

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to exercise the making of robots as opposed to dealing only with theory of robots. In the 80s this approach at the University was a first of its kind.

As a result, and although I was a full-time Professor, I interacted extensively with the industry, and succeeded in securing funding for real-life robotic developments with Northern Telecom, Ontario Hydro, IBM Canada and some smaller companies. It forced me to hire design engineering staff in my laboratory to provide the design infrastructure that could not be accomplished with graduate students. Further on, to expand the scope of these activities and legally separate them from the University, I founded and became the President of Engineering Services Inc. (ESI)—a high-technology company involved in the development of robotics-based automation.

Under my leadership, the company has achieved significant growth and a global leading role in a wide range of industrial sectors. In 2000, the company business in robotics for biotechnology was acquired by an Ontario-based publicly-listed (TSE) company. From 2000-2001 I was also the president of Virtek Engineering Science Inc. (VESI), a high-technology company formed after the acquisition of part of ESI. In 2006, I also founded (and became president of) Anviv Mechatronics Inc. (AMI) a high-technology company involved in the development of mechatronics products. The acquisition in 2000 had provided the means for complete early retirement; I did not follow through because of the love of the profession and my personal attachment to the field of robotics.

With the increase in my business activities, it became quite challenging to concurrently devote the time to my duties at the UofT that I felt was required. The departmental chairman had provided great support, but in the end, I opted for early retirement. It had been very rewarding, and I left knowing that I had put the school on the map and created a new field (robotics) in the University.

The fundamental roles of universities in terms of basic research versus applied research and how well it prepares students at the graduate

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High Payload Robot Arm

HYDRAULIC ROBOT ARM FOR HIGH PAYLOAD HAZARDOUS TASKS

Utility companies must provide tree trimming near live aerial electrical distribution lines to avoid outages due to ruptured cables caused by erratic motion of tree branches during storms and other natural causes. The operation of tree trimming is usually done with hydraulic wood cutting tools by a trained operator stationed in a bucket mounted at the end of an "aerial boom" of approximately 45' in length. The boom is a two-link hydraulic arm with up to four joints that is mounted on a specially retrofitted truck. Two sets of controllers for the aerial boom are used in parallel: one in the operator bucket, and one on a panel aboard the truck, where a second operator (usually the driver) provides guidance and support from the ground. The operator has the ability to lift the bucket to a height of approximately 45'.

Slave manipulator mounted on the aerial boom

The operator carries in the bucket a set of tools: circular saw, linear saw, grappling hook, etc. The operator can connect one tool at a time to the source of hydraulic power available on the bucket. The tools are hand-held, and the operator can perform the cutting operations as needed.

The above-mentioned operations have been proven to be dangerous for workers. Occasionally the operator's tool touches live cables, and due to grounding of the boom and bucket, serious injuries of the operator result. There are also cases where the bucket, the upper boom, or the operator contacts the cables. It should be noted that in most cases the cables carry 22.5 kV. While there is insulation, and grounding is assumed to be avoided, there are instances where the configuration of the system and the work of the operator generate electric shocks to that person.

In response to concerns for worker safety, a remote master-slave hydraulic manipulator was developed with the intent of relocating workers away from the hazardous tasks. The operator is located on the truck platform away from the hazard, and is provided with a hand-held controller (the master) which controls the slave (a new five -joint hydraulic manipulator) that is attached at the end of the aerial boom, replacing the bucket where the operator used to be located. To control the slave the operator uses a second hand-held controller that is a replica of the slave. An assortment of hydraulic tools can be attached to the slave to enable its use in a variety of high-risk tasks.

The slave is a five-DOF hydraulic manipulator arm, and the master is a five-DOF electric arm shaped as a reduced-size replica of the slave. The master is instrumented to provide the operator with torque feedback with respect to two axes of rotation. This allows the operator to feel the forces and moments along and about certain directions at the contact between the tool and branches. Such capability could be extended to a complete (six DOF) force and moment reflection onto the master. The communication between the master and slave is via a fiber-optic cable to ensure electric isolation between the tools and the ground equipment. ■

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level for roles in industry have always been a major concern for me; this concern is still there. My experience and career path would allow me to propose and support a preferred model of university research-industry interaction as discussed elsewhere in this article.

ENTREPRENEURIAL STAGE I

ESI grew into an exclusive small entity with international recognition and a wide range of advanced technologies protected by a large portfolio of patents.

ENTREPRENEURIAL PHASE 2

Emerging applications of intelligent robotics and automation can be found in several sectors such as space, operations, security and medical as decribed in this article.

ENTREPRENEURIAL PHASE 3

In May 2015, the shares of ESI were fully acquired by a Chinese Consortium that included my obligation to lead the company, now a subsidiary of the acquirer, for a period; retirement was not on the agenda. The acquisition led further at the end of 2016 to a public offering in Hong Kong. I became an Executive of a Public Company as Chief Technology Officer.

CONCLUSIONS, PART 1

I have experienced great learning, great employer – Canadarm, great academic life, and great business opportunities, and great family life; no complaints and I am extremely thankful. What made it possible? Personal initiative, no dull day and no static day, trust in gut feeling, great learning, great support at critical times, great life partner, natural restlessness, hard work, and some luck to be in the right place at the right time. ■

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About the Author

Dr. Goldenberg is the founder of the field of Robotics at the University of Toronto where he has been since 1982 as a Professor of Mechanical and Industrial Engineering (now Emeritus), cross-appointed in the Institute of Biomaterials and Biomedical Engineering, and formerly cross-appointed in the Department of Electrical and Computer Engineering. He has supervised to date many graduate students: 46 PhD and 64 MASc. From 1975-1981 he was an employee of SPAR Aerospace Ltd., of Toronto, working on the development of the first Space Shuttle Remote Manipulator System (Canadarm).

Dr. Goldenberg is also the founder of Engineering Services Inc. (ESI) established in 1982 and operating in the development of robotics-based automation. Under his leadership, the company has achieved significant growth and a global leading role in a wide range of industrial sectors. In 2015 ESI was acquired by a Shenzhen-based Chinese consortium, and as of November 2016 the company become publicly listed in Hong Kong. Dr. Goldenberg is the CTO of the public company.

Acknowledgements: *The illustrations for this article come from the three different robotics corporations that I am CTO of. The task of collecting — and in some instances enhancing — them has been a major undertaking. Much of this was achieved through the efforts of Mr. Ken Tang, patent specialist at Engineering Services Inc. His assistance has been greatly appreciated.*