SURGICAL ROBOTICS: THE HAPPY ACCIDENT IN MY LIFE

Inaugural lecture given to mark the assumption of the position as Professor of Surgical Robotics at the Faculty of Engineering Technology (Department of Biomechanical Engineering) at the University of Twente on 29th November, 2018 (Thursday) by

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Everyone has a story about how they got to where they are today. My story of being and becoming Professor of Surgical Robotics in the Department of Biomedical Engineering (Faculty of Engineering Technology) at the University of Twente (UT), Netherlands is best narrated as a journey that commenced a few decades ago from Ahmedabad, one of the largest cities of India. Born in an academic family, I grew up to be a citizen of the world “crossing seven seas and thirteen rivers”... as the saying goes to imply a long, long journey. However, I must say that my career path did not have a clear route map. It had a few rocky bends and twists en route and some happy accidents.

THE BEGINNINGS
I grew up on a beautiful and green institutional campus design by the renowned avant-garde architect Louis Kahn. My father was a professor of Management at this institute of national importance. He held several long term academic positions in Europe and North America from time-to-time. Therefore, I had the opportunity to travel and be schooled in different countries from a very young age.
From a very early age in life, living around academics had a profound impact on me and I believe subconsciously led on this academic-journey. At home, there was much emphasis on excelling in scholastic pursuits.

I started Kindergarten in Freising (a beautiful Bavarian town on the outskirts of Munich). I was speaking German by the time I was five years old, regrettably I have forgotten everything. Our family went back-and-forth between Germany and Canada throughout my teenage years and little did I know that I would come back to study at McGill University in Montreal, where my father was a visiting professor in the 80s and 90s. I call myself a global citizen, maybe that is an euphemism for being a roamer!

**HAPPY ACCIDENT #1**
The first accident in getting into robotics was deciding to study my Master’s degree. I had taken a one year break after my undergraduate studies to see what it would like to work in the real world and ended up working for the Whirlpool Corporation – but I still would not know how to fix a refrigerator, washing machine, or a dishwasher, but I did learn how to work in the corporate setting and prepare presentations on-the-fly. I do not regret this short stint at Whirlpool in the corporate world, albeit a slight detour than a traditional academic career.

I spent a short stint in the late nineties at the Whirlpool Corporation.

I felt I stumbled into the field of robotics. The first person I am grateful to is my master’s thesis advisor (Prof. Arun K. Misra – no relation) at McGill University in Montreal, Canada. My research focused on the dynamics of multibody systems, specifically satelities and large space structures with several flexible appendages. This was really my first experience in
conducting independent research. It was a mentally taxing and frustrating experience but I was high when things would work. This was pure euphoria.

HAPPY ACCIDENT #2
As my Master’s thesis neared completion, I was still uncertain if I really wanted to pursue my doctoral degree. I once again had the urge to take a break from the academic setting. So when I was offered a position as a Dynamics and Control Analyst on the International Space Station Program (at the Canadian Space Agency) – it was an offer I just could not refuse. That is my second happy accident in robotics that would shape my career.

I studied at the Center for Intelligent Machines (http://www.cim.mcgill.ca) at McGill University in beautiful Montreal, Canada.
As a Dynamics and Controls Analyst, I had the opportunity to work on problems that still feel surreal – imagine planning a mission to move objects that are the size of a school bus from space shuttle cargo bay and have it attached to the space station. I was involved in several NASA missions between 2001–2005 as the International Space Station was being built in orbit.

CANDARM2 – The space robot with 7 joints used to assemble the International Space Station.
I worked on the Canadarm2 (Space Station Remote Manipulator System), which was used in assembling the space station. Canadarm2 has 7 joints and moves like an inchworm on the space station. I also did a significant number of conceptual studies for Dextre (Special Purpose Dexterous Manipulator), before it was launched. Dextre is a dual-arm robot with 15 joints. I had the privilege of working with some of the most creative robotic engineers I have met, eagle-eyed flight directors with nerves of steel who could multi-task the various complexities of running a mission into space. They were inspirational managers at NASA who got the best out of everyone while meticulously focusing on details. My experiences while working on the space station program has really influenced my approach to working in large and complicated projects. In spite of my memorable time in working on space robots, I had the itch to learn more and better myself.

DEXTRE – The space robot used for repairs on the International Space Station. It has two arms and 15 joints.

HAPPY ACCIDENT #3
So, fortuitously I applied to the doctoral program at the Johns Hopkins University to work with the renowned haptics researcher Prof. Allison M. Okamura – and I was admitted with full funding. So moving to Baltimore (USA) to study at Hopkins was my third happy accident in robotics and solidified with my path into the research of surgical robotics. I conducted
my research in the Laboratory for Computational Sensing and Robotics at Hopkins and went through all the emotional cycles that a graduate student faces trying to complete a doctoral thesis. The competition was very healthy but fierce, and the drive of my fellow doctoral students was contagious and motivated me to work hard. My doctoral research was at the interface of robotics and solid mechanics, and my dissertation was titled – Realistic Models for Surgical Simulation and Planning. The nature of my research enabled me to be mentored by Prof. K. T. Ramesh (an expert in the field of dynamic failure of materials and biomechanics). After close to five years at Hopkins, I saw the light at the end of the tunnel and defended with my doctoral thesis in May 2009, and graduated with my PhD degree a few months later.

I obtained my doctoral degree from The Johns Hopkins University in Baltimore, USA. I conducted my research in the Laboratory for Computational Sensing and Robotics. (https://lcsr.jhu.edu)
HAPPY ACCIDENT #4
As life takes on not-so-apparent twists and incredible turns, I was offered a tenure-track Assistant Professor position, and the offer seemed attractive. That brings to my fourth and final happy accident – moving to the Netherlands beginning my academic career in August 2009. At UT, I lead the Surgical Robotics Laboratory (SRL), and the overarching aim of the lab is to develop novel techniques to reach challenging locations within the body.

I direct the Surgical Robotics Laboratory at University of Twente. (http://www.surgicalroboticslab.nl)

About three decades back researchers first attempted to improve surgical outcomes by using robotic technology. And slowly but surely clinicians and patients are accepting that this is a compelling apparatus for precisely performing the interventions. The first surgical robot was a tailor-made industrial robot used to direct a needle into the brain. The first well-known surgical robots (ROBODOC® and Acrobot) were designed for orthopedic surgery. This was followed by Probot for prostate surgery. These efforts led to a multitude of academic centers and research institutions undertaking research in the field of surgical robotics.
ROBOTIC MINIMALLY INVASIVE SURGERY

Laparoscopy is often used interchangeably with minimally invasive surgery. The first documented use of the laparoscopic approach dates back to early 20th century in Germany and Sweden. The advent of the computer chip-based television cameras was a pivotal event in the field of laparoscopy. This technological innovation provided the means to project a magnified view of the operative field onto a monitor and, at the same time, freed
both the hands of operating surgeon, thereby facilitating performance of complex laparoscopic procedures. However, these procedures are ergonomically difficult to perform due to the use of long, rigid instruments coupled with the misalignment of visual-motor axes.

It was envisioned that robotics could bring improvement of surgical skills and minimize patient trauma. This idea was the stepping stone for early research in teleoperation, and the development of miniaturized tendon-driven surgical instruments. This work resulted in the two very innovative surgical robots – the Zeus by Computer Motion, and the da Vinci® from Intuitive Surgical.

The Zeus system was used to perform the first transatlantic telesurgery between New York, USA and Strasbourg, France. But in 2003 Computer Motion (the company that developed the Zeus system) merged with Intuitive Surgical, and the Zeus system was discontinued. The da Vinci® system has become synonymous with medical robots worldwide and is now the global market leader.
As da Vinci® achieved commercial success, research and development by academia and start-ups intensified. Flexible snake-like robots and microrobotic platforms are emerging and are expected to further improve surgical outcomes and blur the boundaries between prevention and intervention.

In spite of the commercial success of da Vinci® and its mainstream use in clinics all around the world, surgery as it stands today is still quite invasive for patients. And that brings me to my research area of Surgical Robotics.

The way I think about doing this is by first developing pre-operative plans of the intervention. Using a variety of imaging techniques such as magnetic resonance (MR), computed tomography (CT) or ultrasound, I develop a roadmap of the intervention. These include both developing the path the robot would take to reach the target and also computational models. This is the first approximation of the intervention. This is followed by then using these plans and models to intra-operatively control a variety of instruments,
which include flexible needles, a range of continuum or snake-like devices. And then going down several orders-of-magnitude, I am also interested in trying to track, control, and steer microrobotic systems.

When I started my career in at UT in August 2009, I had a window-less little lab in Carre. I am grateful that Prof. Dr. Peter Vooijs, Dr. Heleen Miedema, and Mr. Remke Burie within MIRA – Institute for Biomedical Engineering and Technical Medicine, who were generous in giving me lab space and have supported my research over the years. I started SRL with a one Advanced Technology undergraduate student and a Mechanical Engineering master’s student. And today the lab has grown to a sprawling space in Horst. I also have lab space at the University Medical Center Groningen for conducting translational research.
Currently there are three main research thrusts within SRL – Needle Steering, Continuum Robotics, and Medical Microrobotics. The first question you might have is why am I interested in needles. So needle insertion into soft-tissue is one of the most common minimally invasive surgical intervention. Needles are used for diagnosis; some examples include biopsies in the breast or lung. Or also for deep brain stimulation or stereotactic neurosurgery. Needles are also used for therapy. Some examples include liver ablation or prostate brachytherapy, where the needle is inserted to basically heat and kill the liver cells, or place radioactive seeds at specific locations within the organ to destroy cancerous lesions, respectively. Needles are also used in fetal procedures, to treat ailments when the child is still in the womb.

As you can probably guess, in all of these interventions the needle must reach very specific locations within the organ. However, needle deviation occurs due to organ deformation or physiological processes such as respiration or fluid flow. Needle misalignment can lead to traumatic or even fatal outcomes. So one of the ways to mitigate needle targeting errors is by being able to steer a flexible needle around obstacles while compensating for uncertainties. An innovative solution would be to have a flexible needle with an asymmetric tip. When the needle with the symmetric tip is inserted...
into tissue it does not bend. But a needle with a kink or an asymmetry is inserted into tissue, it naturally starts to bend due to the presence of the asymmetric tip forces. Now if you rotate the needle, the forces would act in the opposite direction. This idea was actually motivated by discussions with some radiologists – some of whom actually pre-bend the needle before the inserting it. But asking a clinician to do needle steering is quite challenging and it requires extensive hand-eye coordination. So what we have developed are robotic techniques to steer flexible needles.

The MIRIAM robot is designed for interventions in the prostate and can be used inside the MR scanner.

Over the years, SRL has built and tested a range of systems and control methods to steer needles while avoiding obstacles, compensating for organ motion, and also steering needles on non-flat surfaces both in gelatin phantoms and also in animal tissue. We have also done remote steering to understand the effects of needle steering with the human-in-the-loop. Experiments were done with the user/human in Italy while the robotic system was here in the lab at Twente. In order to bring needle steering to the next level and to demonstrate that it can be used for patient care – We have developed systems that be used inside the CT scanner and performed experiments on human cadavers for lung and liver biopsies. Also we have developed MR-compatible systems for interventions in the prostate. I think we are at the stage where we can start pre-clinical trials with our needle steering systems, and this is really an exciting time in the lab.
More generally, I am also interested in designing and controlling continuum or snake-like robots. So when one thinks of robots one generally imagines industrial robots with rigid links. But I am interested in developing and controlling robots which have unlimited steerability. These robots are either be tendon-driven or can be magnetically-actuated systems. Our application areas are in endovascular and endonasal interventions, cranial procedures, and also endoscopy. We have developed several systems that can be autonomously tracked and steered. These devices can be tracked not just with clinical imaging modalities but we integrated fiber optic sensors along the flexible robot so that we can track them in real-time.

Continuum robots usually comprise of a series of flexible elements, which bend continuously. The dexterity, flexibility, compliance, and soft-structure of the continuum robots make them inherently safe to use in clinical practice. Such mechanisms permit for much more complex dynamical behavior than the one observed in classical, rigid-link robotic manipulators. At SRL we work to understand the behavior of continuum-style devices, and developing advanced mathematical models for them. Subsequently, we exploit these models in closed-loop control strategies, which assist the clinicians in their task. Among other work, we successfully demonstrated a tendon-driven catheter for ultrasound-guided mitral valve replacement. This catheter uses advanced model-predictive control to compensate for heart motion, making the beating heart appear stationary for the surgeon.

Our ultimate goal is to develop safe and reliable continuum-style surgical tools capable of reaching deep-seated regions within the body. Therefore, we actively search for new architectures of continuum robots, which allow for successful operation at smaller scales. We are one of the few
research groups that have successfully used magnetic actuation for that purpose. Magnetically-actuated continuum robots are fitted with magnetic material, which reacts to an external magnetic field generated by an array of coils located outside of the human body. By successfully combining this actuation technique with our research on modeling and shape tracking, we are capable of creating continuum-style robots, which can be wirelessly controlled regardless of their location within the human body. Furthermore, we actively explore the possibilities given by magnetic actuation, developing advanced reconfigurable continuum robots for complex surgical tasks. Examples would involve a bio-inspired tentacle catheter for biopsies and polyp removal, and a series of reconfigurable continuum robots capable of worm-like motion under external magnetic fields.

In line with our lab’s motto to develop novel techniques to reach challenging locations within the body – one can imagine that a flexible needle or a continuum robot could be steered around obstacles and precisely reach a target, and then one releases micro- or nano-robots that can deliver the drugs or perform the interventions remotely. And that brings me to the third research thrust within SRL – Medical Microrobotics. At SRL, we develop magnetically-steered minaturized robotic systems.

A flexible instrument can be steered around obstacles to deliver a range of diagnostic and therapeutic magnetic micro-robots.

Through numerous studies we have designed, built and validated a wide number of microrobotic devices and control approaches. Long before the widespread media attention that focused on microrobotics in recent years, we have investigated the precise control of single microscopic particles,
and subsequently successfully challenged ourselves to demonstrate the
use of clusters of microparticles for micro-assembly tasks. Moving from
there we have investigated the use of innovative fabrication and control
technologies for steering a range of microrobots, e.g., magnetosperm,
microjets, janus particles, and magnetotactic bacteria.

A bio-compatible and thermally-actuated microgripper that could be used for biopsies.

However, we knew that three constraints were hindering the real-life
application of this technology: Lack of dexterity, constraints in two-
dimensional (2D) environments, and clinically-compatible imaging.
Determined to tackle these challenges, we collaborated with a cutting-edge
lab at Johns Hopkins University in nano-fabrication to develop hydrogel
and metallic grippers with sub-mm footprint. By embodying these grippers
with “intelligence”, we were able to demonstrate fully autonomous in-vitro
pick-and-place of organic tissue, even in unstructured environments and in
the presence of dynamic obstacles. Through this collaboration, and a few
adjustments, we rendered these grippers visible in ultrasound imaging.
Using such a clinically-compatible imaging technique we were able to
control these grippers in 2D. In the meantime, we have been able to break
the 2D barrier and move to the real three-dimensional (3D) world. After
3D motion of a single agent, we demonstrated independent 3D motion of
multiple agents positioned in the same non-homogeneous electromagnetic
field. All these techniques leave one to wonder of multiple ultrasound-
imaged microgrippers collaborating to perform truly minimally invasive
surgery within the body.
In spite of all the advances, surgery is still a very traumatic experience for most people. So what I really hope is having miniaturized microrobots that can perform personalized and targeted therapy. The movie Fantastic Voyage has inspired me in my work. Fantastic Voyage is a 1966 science fiction film. The movie is about a submarine crew who shrank to microscopic size and ventured into the body of an injured scientist to repair the damage to his brain. Though the physicist Richard Feynman was one of the first to propose the idea of manipulating individual atoms in a lecture in 1959 titled – "There’s Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics", it was Feynman’s doctoral student Andrew Hibbs who suggested the use of Feynman’s theoretical micro-machines for medical use. Hibbs suggested that in the future the micro-machines could be reduced to the point where one could “swallow a doctor”.

Because of recent advances in micro-/nano-fabrication, it has been possible to fabricate nano-drillers, micro-grippers, and micro-bullets. We are not far away when we can essentially swallow the surgeon, and use medical nanobots to diagnose and treat diseases from inside the body. Nano-/micro-docs have tremendous potential in the areas of precision surgery, detection, detoxification, and targeted drug delivery. Engineers can add functionalities to nano-materials by interfacing them with biological molecules or structures. Nano-materials have a size similar to most biological molecules and structures; therefore they can be used inside the body, even down to the level of a human cell. By combining nano-materials with biology,
ingenious engineers have developed nano-scale diagnostic devices, contrast agents, analytical tools, and drug delivery vehicles. Despite the many challenges, engineers have successfully demonstrated a variety of medical nano-robots that can navigate through complex biological environments. These prototype nano-docs have been able to remove biopsy samples, deliver drugs and even diagnose diseases. Additionally, delicate surgeries such as those of the eye are only performed successfully by a few skilled surgeons. Immense risk is involved in these delicate surgeries and they require a steady hand. It may soon be possible to take the human element of risk out of this equation by introducing nanobots. Moreover, micro surgery of the eye as well as surgeries of the retina and surrounding membranes could soon be performed using nanobots. In addition, instead of injecting directly into the eye, nanobots could be injected elsewhere in the body and guided to the eye.

In order to realize my fantastic voyage dream, I cannot do without a close-knit team of researchers. I am privileged and honored to have mentored some brilliant and tenacious post-docs, doctoral students, bachelor’s and master’s students from Twente and around the world, who have spent time in our lab. I have learnt so much from my collaborators, both academic and clinicians, who have motivated my work and inspired me to come up with new solutions. Special thanks to Prof. Dr. Bart Koopman and Prof. Dr. Geert Dewulf for their unfettered and unconditional support from the Department of Biomechanical Engineering and the Faculty of Engineering Technology, and the University of Twente. Were it not for this support and the hard work from my mentees, the fruits of my work done thus far would perhaps have remained a piper’s dream.

I would probably not have chosen the academic path were it not the guidance and motivation from my parents who live thousands of miles away but whom I can always count on for timely advice. I am grateful for this. I am forever in debt for the affection and care that Raffaella has provided. Last but not the least; mere words do not express my appreciation and gratitude for the genuine love that Neel consistently provides and showing me what is really important in life. I am forever grateful for their presence in my life.