Alexander von Humboldt Professorship
Five Years Told in Nine Projects

Robotics and Biology Laboratory
Dear Colleague, Dear Scientist, Dear Friend,

In 2009, after sixteen years at US universities, I returned to Technische Universität Berlin. This decision was made easy by the fact that I had been awarded an Alexander von Humboldt Professorship. The goal of this program, implemented by the Alexander von Humboldt Foundation, is to entice scientists to come work in Germany. The award comes with a substantial research prize, which funded many of the scientific activities of my lab over the course of five years.

The Alexander von Humboldt Professorship enabled my team to conduct research in an unconstrained manner—in a manner that sparks creativity and motivates deep thinking. It enabled my team to pursue risky, maybe even somewhat crazy ideas, to develop novel ways of solving long-standing problems, to break with traditions, and to build an excellent infrastructure for the future. As you can imagine, these five years have been a thrilling scientific journey for my team and for me. The experiences during those five years have shaped me and the activities of my lab in ways I never imaged possible.

This brochure serves as a final report for this amazing five-year period, in fulfillment of the requirements of
the Alexander von Humboldt Foundation. However, I would also like to see it as a token of appreciation, as a way of expressing my heartfelt gratitude towards the Foundation and the people that have helped me along the way.

Of course, this fantastic research prize and the opportunities associated with it also laid a weight of responsibility onto my shoulders. I felt pressure to deliver on the expectations associated with such a distinction. So in some ways, this brochure therefore also takes stock of our accomplishments, in an attempt to demonstrate that the vote of confidence was justified.

I hope that you will find the information provided in this brochure stimulating. It highlights some of my lab’s activities over the past years. Furthermore, I sincerely hope that you will come away as a strong supporter of the Alexander von Humboldt Professorship as a funding program so that other researchers can come to Germany and benefit from this life-changing opportunity.

Sincerely

Oliver Brock
Breaking New Ground with Unbreakable Fingers

My lab had never designed or built novel robotics hardware before. Our mobile manipulators consisted of off-the-shelf research manipulator arms mounted on mobile bases. But when these mobile manipulators started roaming our lab, attempting to grasp things, we noticed one big drawback of existing robot hands: they were made out of metal! Hard, slippery, and dangerous. The fingers of these hands were not able to gently wrap around the objects they grasped. Rather, they forced the object to adopt the shape of the hand, often damaging it in the process.

We decided to build a totally different kind of robotic hand—a hand that is entirely soft so that it can comply to the shape of the object it grasps! This hand turned out to be highly capable, easily grasping many things without damaging them. Even though they are soft, it is surprisingly dexterous: We showed that the hand can replicate nearly the entire Feix grasp taxonomy, an inventory of human hand postures. And even though it is soft, it can be surprisingly strong: The hands we build can lift more than five times their weight, and we could easily make them much, much stronger. And even though the hand is soft, it is
surprisingly dexterous and even capable of in-hand manipulation!

Because the fingers are made out of rubber and are operated pneumatically, they are nearly indestructible: they work under water, in dirt, or in dust; or after a truck drove over them. And if you accidentally pierce the rubber, all you need is some silicone glue to fix them. Building a hand only takes a day, and the materials cost less than 10€. Our RBO Hand 2 is now used in several research labs around the world, including UC Berkeley, University of North Carolina, University of Pisa, the Italian Institute of Technology in Genoa, Disney Research Zurich, Ocado Technology, and the Fraunhofer Heinrich-Hertz institute.

The funding provided by the Alexander von Humboldt Foundation made it easy for my lab to enter the hardware business, even though we had never done that before. An idea was turned into reality in a couple of months and now the researchers in my lab are experts in building soft robotic hands.
Humans manipulate the world around them with incredible ease and dexterity. We cannot say the same of robotic hands. Why is that? Of course, there are many reasons... but we wanted to take a closer look. We filmed students picking up everyday objects and watched the recordings in slow motion. We discovered surprising difference between human and robotic grasping: Humans do not generally use their hands in a very precise manner. Instead, they engage in extensive, large-surface contact with the environment with their hands, slide fingers along surfaces, and basically ignore the minute details of grasping. Robustness and reliability are the result of relying on the physical interaction between human hands and the environment. This stands in stark contrast to the way roboticists have traditionally viewed manipulation.

We have turned this observation into an EU-funded research project, called Soma. Together with five European partners, we are developing Soft Manipulation technology, which we hope will be safer and more capable than existing robotic technology. This would permit the development of a new generation of softer and more human-friendly robots to address novel industrial applications and to work in collaboration
with humans. The funding provided by the Alexander von Humboldt Foundation enabled us to build a new Human Grasping Lab in which we record and analyze grasping trials. We collect lots of data from cameras, a state-of-the-art motion capture system, data gloves, and touch-sensitive tables. We turn the resulting insights about the principles of human grasping into novel robotic technology. Our soft robot hands, shown in the preceding project, are ideally suited for this.
A Robot As Smart As a Cockatoo?

Dr. Alice Auersperg (Comparative Cognition, University of Veterinary Medicine, Vienna) and Professor Alex Kacelnik (Behavioral Ecology, Oxford University) want to understand the cognitive capabilities of cockatoos. They expose them to mechanisms like the one shown on the left: a series of mechanical puzzles that, when all solved correctly and in sequence, give the cockatoo access to food. Surprisingly, some—but not all!—cockatoos can solve the so-called lockbox with less than an hour of exposure to the mechanism. “We do not understand how the cockatoos do this. Why can’t you build a robot that solves the lockbox so that we might understand something about the cockatoo?”, Alex asked me one day.

And so we decided to try. Together with Professor Marc Toussaint (University of Stuttgart), we are working on the DFG-funded project “Exploration Challenge.” We have copied the lockbox for cockatoos so that it has the appropriate size for a robot. We are developing the motor skills, perception capabilities, and exploration strategies required for the robot to face the challenge of opening this lockbox. We are confident that we will be able to make the robots in Stuttgart and Berlin solve this task. And maybe our ability to experiment with our robots will enable Alice
and Alex to test hypotheses about how cockatoos solve the lockbox.

The Alexander von Humboldt Professorship made it possible to embark on this truly interdisciplinary research endeavor. Especially in the context of robotics and artificial intelligence, joining forces with cognitive scientists, neuroscientists, and biologists seems like an important and promising avenue towards insight and progress.
Seeing is Believing—
but Touching is Knowing

Already in the 1970s, James J. Gibson showed that the visual perception of humans improves significantly when subjects also touch and manipulate the objects they are supposed to identify. He used objects like the ones on the left and asked people to find out which two were identical. Can you do it based on the image alone? You certainly could if you were allowed to touch them!

Since Gibson’s experiments, the idea of perception as an active or even interactive process has gained substantial support in several disciplines, for example through the works of the philosopher Alva Noë and the psychologist Kevin O’Regan.

In robotics, this trend is reflected in a research area called Interactive Perception. This field has been very successful in finding robust and versatile solutions to perceptual problems relevant to autonomous manipulation. The research of my lab has played a role in shaping this field and we coined the term Interactive Perception in a publication in 2007. Interactive Perception is now an active area of research with workshops dedicated to the topic, a forthcoming review article—and it is even mentioned in job descriptions.
as a required skill for candidates applying for professor positions.

My lab develops perception algorithms for robots that fall into the paradigm of Interactive Perception. These methods do not treat perception and action separately but consider them as two sides of the same coin. The idea is that the interpretation of a combined sensing/action signal is much more useful for a robot and much more robust than doing the same based on visual perception alone. The image on the right shows one of our robots, interacting with an articulated object in its environment. The prismatic degree of freedom of the drawer is revealed by pulling on the drawer (and would not be perceivable without interaction). Our robot is able to identify interesting interaction points in the environment, excite degrees of freedom through deliberate forceful interaction, perceive these degrees of freedom, and extract a kinematic model of the world. Finally, it can use this model to steer and improve its own actions.

If you think about the cockatoo from the previous page, clearly, the bird must possess similar skills to be able to unlock the lockbox. The algorithms we develop here thus find direct application in our attempts to build a robotic cockatoo.
Each human eye contains approximately 130 million photoreceptor cells. Our visual input, from a computational perspective, therefore consists of a 260-million-dimensional vector—a huge amount of data, generated about 200 times per second. How is it possible for the human brain to turn this sense data into useful perception? And how can we achieve the same for robots? Of course, robots only have cameras with several millions of pixels, sampled only dozens of times per second, but still, the amount of data generated is overwhelming.

The field of representation learning attempts to address this problem. It develops algorithms that extract low-dimensional representations from high-dimensional data. A good representation contains all we need to know and is much more compact than the original sense data. But, of course, "all we need to know" can only be defined in the context of a particular tasks. This means that distinct tasks will require different representations of the sensory data. We therefore need to devise representation learning algorithms that are specific to robotics. And this is exactly what we have done. By leveraging information about Newton’s laws of motion—some general rules about how our world works—we can learn representations
that are well-suited for robots, i.e. machines operating within that world. We use knowledge of physics to disentangle the high-dimensional signal chaos and to turn it into something that enables our robots to act competently.

For example: on the right you see instances of visual input to a mobile robot. Can you make sense of it? Our learning algorithms take any sequences of these images (throw in some of Newton’s laws) and determine the exact pose of the robot.

Representation learning is highly relevant to the overall research direction in my lab. However, it was a completely new research direction for us. Entering a new field is always a challenge and was made possible through the funding provided by the Alexander von Humboldt Foundation.
The Amazon Picking Challenge

Robotics is revolutionizing logistics and commissioning, a field growing quickly due to continuously increasing internet sales. Logistics companies are working on automating the process of order fulfillment, starting from a customer’s order all the way to shipping the ordered items. To achieve this, the order has to be assembled from huge warehouses with shelves containing hundreds of thousands, if not millions of products.

The acquisition of Kiva Systems by Amazon for $775 million in 2012 demonstrated that there is tremendous commercial potential in automating warehouse logistics. In spite of such significant investment, however, the step of taking a product off the shelf and putting it into the shipping container is still performed by humans. The goal of automating this final step is the motivation behind the Amazon Picking Challenge. In this challenge, robots have to assemble a fictitious internet order by picking objects from the kind of selves you find in Amazon warehouses.

Twenty-six teams from around the world participated in the challenge, some from renowned research universities, other from large companies. Our robot, shown to the left, won the competition, gathering
148 points. MIT placed second with 88 points, and Team Grizzly, a collaboration between Oakland University and Dataspeed Inc., placed third with 35 points.

A most heartfelt congratulations to my team, who have not only shown that they are excellent roboticists but also that they can come together as a team and deliver a perfect performance!

One of the keys to our success, I believe, was our extensive experience in mobile manipulation, a paradigm in robotics research that has diverged from classical automation. In mobile manipulation, the emphasis is on building integrated systems that exhibit behavior in real-world scenarios. The goal is to develop systems that can take the leap from factory floors into everyday environments, inhabited by humans.

Our strong performance triggered interest by the media, the public (40,000 YouTube views), and also by some of the largest logistics companies in the world: DHL, Geodis, and TGW Group. This interest demonstrates that basic research can have impact on real-world applications. But without the funding provided by the Alexander von Humboldt foundation, I might have never taken the decision to participate in the Amazon Picking Challenge.
From Robots to Proteins

The Amazon Picking Challenge is not the only competition my team participated in while funded by the Alexander von Humboldt Foundation. Every other year, the global protein structure prediction community engages in a large-scale experiment, called CASP (critical assessment of protein structure prediction). In the 2014 CASP, 208 teams from all over the world predicted the three-dimensional structures of 100 proteins from genetic information alone, in an activity that lasts several months. Here, too, my team has performed very well. We placed third! A statistical evaluation of the ranking by official CASP evaluators revealed, however, that the quality of our predictions was statistically indistinguishable from those of the first- and second-ranking teams.

What does this have to do with robotics? Proteins are long kinematic chains and as such share a configuration space representation with robots. Because of this similarity, many of the motion planning methods my group has developed over the years find application in this domain.

But what is the actual challenge? The sequencing of the human genome (and many other genomes for that matter) has given us an abundance of genetic
information. This information contains blueprints for all the proteins inside our body. And proteins are the basic building blocks of life, performing pretty much all biological functions in cells. But these blueprints do not provide an understanding of protein functions. For this understanding, we must know the three-dimensional shape of proteins. These structures are of stunning beauty, as you can see on the right.

Understanding protein structure is considered the holy grail of molecular biology. Seventeen Nobel prizes have already been awarded in this area—but we are still far from solving the problem. Any progress in this area holds the promise of profoundly advancing our understanding of life and therefore our ability to treat or cure diseases, such as cancer or Alzheimer’s disease.

The computations in protein structure prediction require substantial computational resources. And to be competitive in CASP, we needed a state-of-the-art compute cluster. The funding provided by the Alexander von Humboldt Foundation allowed us to acquire one, indirectly enabling our success.
In addition to the computational approaches for protein structure prediction tested in CASP, there are several major experimental methods, including X-ray crystallography, nuclear magnetic resonance spectroscopy, and cryo-electron microscopy. These methods are either expensive, complicated, cannot address all types of proteins, or all of the above. As a result, we know the sequences of tens of millions of proteins—but we only know the structures of about 100,000 of them. Computational methods, such as the one tested in CASP, are still not capable of closing this gap. We need novel methods for determining protein structures to do so.

Together with Professor Juri Rappsilber and his team from TU Berlin, we are developing a novel method for protein structure determination. The key idea is to bridge the computational and the experimental worlds, taking the best from both sides. The experimental data is easy to acquire—even in the living cell, which would be great novelty! But the data is sparse, noisy, and incomplete. Enter computation: Using the algorithms my team has developed, we can take this data, combine it with knowledge about protein structures in general, and turn it into a protein structure.
Human serum albumin, a protein from our blood, is the first protein structure ever determined with this method.

We are working together with Juri’s team to expand the capabilities of this method, attempting to turn it into an effective and versatile alternative to existing experimental protein structure determination methods. We have a long way to go, both on the experimental and on the computational side. But we are making progress. The images show the data density before (previous page) and after (right) the innovations made by Juri’s team. The substantially increased data density made it possible for us to apply our computational algorithms.

A lot remains to be done. But if we are successful, we will have created a new type of microscope to study the processes inside cells, opening up many exciting opportunities for science and medicine.

My lab may be the only robotics lab in the world that owns part of a mass spectrometer. Of course, this acquisition (for which Juri provided the lion share of funds) was only possible through the funding provided by the Alexander von Humboldt Foundation. Another example of how exciting and truly interdisciplinary research was enabled by this fantastic program!
From left to right, standing: Raphael Deimel, Arne Sieverling, Clemens Eppner, Sebastian Höfer, Vincent Wall, Oliver Brock, Alexander Magraf, Tim Werner, Ines Putz, Peter Lehner, Philipp Bartels, Olga Runge, Mahmoud Mabrouk; kneeling: Roberto Martin-Martín, José Álvarez-Ruiz, Michael Schneider, Rico Jonschkowski; not shown: Jessica Abele, Manuel Baum, Kolja Stahl, Janika Urig
I would like to thank my fantastic team—a group of smart, creative, dedicated, and genuinely awesome people. They have not only made all of it happen, they have made it a lot of fun! They are the ones who deserve all the credit. And they amaze me every day!

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