Pisa, Italy
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Paolo Dario

An interview conducted by
Peter Asaro

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Q: If you could just start by telling us where you were born and where you grew up and went to school.

Paolo Dario: Ok, well first of all my name is Paolo Dario. I am now a professor of biorobotics at Scuola Superiore Sant'Anna in Pisa, Italy. I was born in Piombino, a small town just in front of the isle of Elba in Tuscany that was inhabited by Etruscans, and then by Romans, and also by Napoleon actually, and I went to school there. Then I moved in different parts of Italy, and I got my university degree in mechanical engineering at the University of Pisa in 1977. And after that I had to serve in the military for one year, and then I started almost by chance actually my research activity also at the University of Pisa and in the field of biomedical engineering. Actually my thesis was also on biomedical engineering, and I was interested in biomedical engineering, although my degree was in mechanical engineering, because I wished to do something useful for mankind. I was always interested in the usefulness of what I was doing. I would say that I've been always interested in merging science and engineering. I could define myself a true engineer. That is, I always look for objective, for results, for usefulness rather than for pure new knowledge. I'm interested in new knowledge but to the extent that I know it could be useful to solve practical problems. In this process I like, and I'm able, even if I didn't know a priori, that I'm pretty good in devising new solutions, be creative, and this has been sort of like motive and continuous guidance in my career.

Q: What was your graduate thesis project?

Paolo Dario: It has been in the design of a new artificial heart, a pulsatile artificial heart that was intended to overcome the limitations of artificial hearts available at that time. So I learned a lot about design, about modeling, about sensing even if at that time sensing was not as common as today, but I got interest in that area. It is very interesting to notice that after 40 years, actually even more, I've been able to get a project on artificial heart right now that is closing the circle. This teaches to me a lesson that there is always a time, sometimes you can do things too early, but if you have vision and also perseverance, the right time comes, so I am working now on my graduate thesis again. A different perspective and it might be also with more chances of being successful. But this is also a lesson for our students listening to this talk. Be perseverant, and the right time almost always comes, even when you do not expect.

Q: Who was your thesis advisor?

Paolo Dario: My thesis advisor was an Italian professor, an engineering professor, Giancarlo Nardi, but I also got many good hints from other senior colleagues, who are now also professor colleagues and medical doctors also. I think my life in a way changed at that time, because I would say after my thesis really than before. I must say that at that time in Italy we didn't have any PhD courses strictly speaking. The first PhD courses were introduced in 1982 or so. We completed our education through quite a long sequence of the equivalent of BS and MS plus sort of training, the post-degree training. So in total actually, I got almost nine years of education in total at that time almost one decade actually, in mechanical engineering but also in biomedical engineering as a sort of specialization, mostly in Pisa at that time. I must admit just to be clear that I traveled for the first time in my life on an airplane at an age of 29. It would be sort of incredible today, of course I traveled a lot using my motorcycle, because I'm still a biker, this is my passion, but not much before. So my education, I travel in Europe also but never in the U.S., and I had an education that was international in vision and aspiration but not much in a real traveling. But I must say that even at that time, Pisa, in some departments, some research centers, was deeply international. For example there was an institution, I owe very much to it, the Institute of Clinical Physiology or the CNR. The CNR is the National Research Council of Italy where I learned really a lot working with biomedical engineers, physicists, mathematicians and many, many doctors. And it was a very nice community where I learned the interdisciplinary research very much and international opening to new ideas, to new inputs. I have always been prone to have a very open mind, not too sectorial. So I'm curious, very open to good ideas, hints coming from everywhere rather than from my own specific field. And then at that time, I learned a lot. So I learned working with sensors because from the artificial heart I was likely moved towards sensors. Sensor technology – so sensor to measure pressure, to measure flow, to measure vibrations, accelerations, noise, any kind, mostly physical parameters because I'm still a mechanical engineer as a background so I like physics. And sensor technology is a very, very good gym for education of engineers because it's very, very interdisciplinary.

In order to design a sensor, you need to have good understanding of many different phenomena and using different things, so modeling, materials science, microelectronics, single processing, measurement technologies. So you become aware of many different problems and you are able to integrate them because the sensor, today, we are no longer talking about sensor. We are more and more talking about MEMs and microsystems and, in fact, they are sort of micro machines, if you will, micro system integrating, mechanical parts, actuators, sometimes, sensor themselves, electronics, then control, communications. Sensor technology is very, very good for training. And I learned a lot by working on sensors for a few years in many different areas. The problem of sensors is that the sensor experts are – they depend on the needs of different people. So they had their own technology, their own abilities. There is a community. I'm part of it, also a big part, and still I'm part of it. But they are either discoverers, inventors in search of an application. Or I would say they implement – people who can implement problems that are created by others.

But through the sensor pathway I moved from the core of biomedical engineering into robotics. So I entered the field of robotics through the door of the sensors because while developing physical sensors like pressure, temperature, vibration, sensor, acceleration sensors I learned about robotics. I was not really aware about robotics before 1982. I met many, many bright colleagues, and masters, let's say, who really advised me that this could be a good area for research, of course, for application. And also for science. So robotics gradually became my main field of interest because robotics is extremely wide. And so it was a very appropriate field for my own attitude, so looking at problems with a large extension.

For example, if you look at these robots here, there is everything here, from sensors, to the actuators, electronics, control, intelligence, sensing, in fact, a vision and communication and usefulness. And there's a mechanical structure that I like something like my motorcycle. Or those are just electromotors but they can move. I like motion capabilities amongst other things. So sensors were the gateway for robotics. And my first research in robotics was on tactile sensing because these colleagues that I met at that time advised me that robots needed tactile sensors, artificial skin. They didn't have artificial skin. And it's easy to understand that the sense of touch is very strong in biological systems. I would say all living beings need and have contact or more sophisticated contact sensor like tactile sensors or skin, able to detect different kinds of contact passively, but more frequently, actively. So the sense of touch is an active sense. It's not relatively passive as hearing, for example. You have to search for information. So the sensors use similar technologies as pressure sensors, in biomedical engineering, and this was where I came from. But they have many different functions related to manipulation and to active search so essentially, perception and intelligence, if you will. So gradually, I became interested, not only in the sensor, but also in the fingertip, in the finger, in the hand, then in the arm and finally, in the full body of the robot. And this was what I gradually developed and became the core of my research interest in the late eighties and in the nineties.

I should also say in the eighties I was able together with a colleague of mine in Pisa, who is now a professor, Danilo De Rossi and people in the CNR and the university this is – when I said that even if I always studied in Pisa, Pisa was a place where I could meet virtually everybody from every part of the world. It was already very international. So I met two people who really changed my life. One is the late professor Pierre Galletti, and professor Peter Richardson, both from Brown University. And through them finally, I took a plane and I visited my dream country that was the U.S. So in 1980, I was finally able to fly to the U.S. And then I flew maybe more than a pilot, sometimes. So now top frequent flyer. I just say reconsider all of my previous staticity. And now I'm a very frequent traveler. And we started the collaboration with a very big company, Johnson & Johnson at that time. So we even create a partnership. So Pisa, Providence because Brown University is in Providence, Rhode Island. And I spent a lot of time also with my family. By the way 1977 I married my wife, still my wife, only one wife, Laura. And I got two daughters in those years. And so we went together to spend time in Providence from 1983 to 1986 or '87 I was an assistant professor in research at Brown University.

And we worked together with a group of biomedical engineers there and medical doctors in the development of a variety of applications of piezoelectric polymers. You still remember my background in sensor technology for medical application but also for robotics application. And that period, exactly, in those years, I moved from biomedical engineer more and more towards robotics. And then in 1985 and '86 and '87, I was one of the first participants in ICRA. ICRA is now the International Conference of Robotics Research. The first conference was in 1984. It was at that time, it was the council and not an IEEE society. Immediately afterwards it became an IEEE society and the first ICRA conference was in 1985 in St. Louis. And I had always attended ICRA from that time on. And I met and I became familiar with many, many nice colleagues who are still good friends from Oussama Khatib, Ken Salisbury, Tomas Lozano-Perez, Tony Bejczy, Ruzena Bajcsy, Mike Brady, Georges Giralt, Hirochika Inoue, Toshio Fukuda. And I cannot, of course, list of all of them but all of them are very good friends, colleagues, still. We enjoy meeting, collaborating. At that time, I would say really we created the community of robotics.

We were all young, more or less, some really young, some mature. But the community was very young, very enthusiastic willing to open a new frontier, a new field. In this sense, we really were the pioneers of robotics, even if it's difficult. At that time, we didn't realize entirely this but there was a lot of enthusiasm. Everything was to be discovered. Marc Raibert made this hopping robot. And all of us worked in different fields. I would say at that, my specialization was essentially tactile sensing. Ruzena Bajcsy was very good in vision. And Ken Salisbury designed his hand and Oussama Khatib was an excellent controller and so on. Again, I don't want to forget distinguished colleagues, but just to name a few. So the community was growing and we were achieving very good results. And every conference, actually every six months new things were implemented or discovered sometimes and invented and implemented and demonstrated. And it was so nice. At that time, we used the VHS video thing and we could see that for the first time the implementation.

And so I also became a close collaborator of Ruzena Bajcsy at the GRASP Lab. And we worked together on hands, on perception, tactile sensing. I spent years collaborating with her, the University of Pennsylvania, and Philadelphia. She came, actually, we hosted many, many courses. All of the members of the robotics community, more or less, came as visiting professors in Pisa. I should also say that in 1983 I became formally an assistant professor at the University of Pisa with tenure. And then in 1986 I became an associate professor with tenure of biomedical engineering at the Scuola Superiore Sant'Anna. And then in 2000 it took a lot of time because in Italy those things are quite unpredictable I became a full professor at Scuola Superiore Sant'Anna. And meanwhile, I was a visiting professor in many different places, visiting, meeting, organizing conferences; I think it's interesting and a very good suggestion also for young researchers.

There was one person who also probably changed my life. So one I think was Tony Bejczy. Tony Bejczy I met him in 1982 in one of my early trips in the U.S. and with the robotics mostly robotics community. At the time I met Lou Paul it was in Purdue University. And then there's the Pennsylvania. But I also met Tony Bejczy at that time. He was at JPL. And he was really very, very nice in advising me, again, to continue on tactile, the development investigating of touch and development of tactile sensors. At that time I also wrote very fundamental papers on tactile sensing including one on Spectrum, IEEE Spectrum. It was really very often cited. It was one of the most cited early papers on tactile sensing in robotics on active touch, active tactile sensing. So the concept of active touch was introduced by me and colleagues at that time. And so after this meeting with Tony Bejczy actually he invited me in next conferences. For many years, I was the only Italian participating in robotics conferences and also working with IEEE because IEEE was the main society, of course, organizing. We were the founders of the robotics and automation society. And Ruzena Bajcsy was another person who really advised me.

And another person that few of us remember was Jean Vertut. Jean Vertut was a French scientist, who was a pioneer in tele-operation. He worked at CEA, that is the nuclear agency or energy agency in France, Paris. And he essentially invited me. He proposed me to organize a NATO workshop in robotics. In that period of time, '82, '83, '84 it was the flourishing of many organizations in robotics. And one of them was IRP, International Advanced Robotic Program, of course, RAS, IEEE RAS. Also ISRR, the International Symposium of Robotics Research that was very strongly for only invitation and I was honored to be invited. I'm now a permanent member of the board there. And at that time, Jean Vertut advised me to organize this workshop promoted by NATO, NATO scientific workshop, of course. And I organized two such workshops in 1986 and 1989. And I edited the books that came out of these workshops. And if you read and I'm glad to show to my students, the names of the people who attended those workshops, especially the second one. And you can see, all of the roboticists, all of those who are famous in robotics now were there. So these were funding events. And I owe to Jean Vertut, I was hesitating because I was very young, and I thought I was inadequate for organizing these workshops. He encouraged me very, very much. We had a meeting in Paris. He said, you will never say – you will always remember positively these efforts or do this. And just the one week after we had this meeting in Paris unfortunately he died of a heart attack. But I want to remember him as one visionary who had really this attitude of encouraging young person to dream and to be part of this growing area personally.

And so in those years I also developed my own laboratory I should say this because my group, of course, I was alone. I was traveling. I was studying. I was doing research alone, but I was also educating young collaborators. And I was in that period toward the end of the eighties. In parallel with this international networking with this increasing responsibility in organizing events, I mentioned these workshops, but in 1991 I organized or accepted in 1989 to organize one of the first ICAR conferences. ICAR stood for International Conference of Advanced Robotics. I organized this conference in Pisa in 1991. And we had 501 participants, which, you know, is huge. And, again, if you look sometimes I do old pictures, slides, again, you can find literally all robotics community there. And my own group grew very much in those years.

In 1989, I created the ARTS Lab. ARTS stands for Advanced Robotics Technology and Systems. So also pointing out the work advanced because we didn't work very much in automation or in industrial robotics. It was mostly nonindustrial robotics. Technology because we like to build real stuff and to have our own technology, very advanced technology and system because we like to integrate different components into systems. And then in 1991, I established the second laboratory at Scuola Superiore Sant'Anna called the first MiTech and then CRIM lab which stays for laboratory for micro technologies and micro robotics. Both of these laboratories have been fused this year in the new Institute of BioRobotics that I have the privilege to coordinate. And we are now about 160 people working on a variety of topics, with about 80 Ph.D. students on board, which is a huge number and doing different things.

Q: Okay. I just want to go back a little bit. So in terms of the social connections, so when did you meet, say, Ruzena Bajcsy for the first time? Was it when you were already at Brown? Or had you met her at these IEEE conferences?

Paolo Dario: I think I met her first in 1984 at this first robotics, international robotics conference. It was nice because I remember, I was introduced by Tony Bejczy. Tony Bejczy from Hungary. Ruzena Bajcsy from Slovak Republic at that time. And there was another colleague who was a very good mathematician expert in algorithms. I don't remember the name now but we sat together and the three of them were from formerly, let's say from Eastern Europe. And they were in the U.S. as refugees, I would say, very high quality refugees. Yes, I met her at that time 1984. And then we became good friends and also really colleagues in the working together. She came to Pisa many times. I went to Philadelphia many times.

Q: Were you a participant at all in the Romansy conferences?

Paolo Dario: Not so often I must say but a couple of times. Also on that there is an interesting story. I think it was exactly 1984 also or '83 or '85, and I met many, many very nice, very good people, Bernie Roth from Stanford. Also Oussama Khatib was there. Bruno Siciliano was a young student at that time and also Atsuo Takanishi. Professor Kato was there. I became very good colleague of Professor Kato and his student Atsuo Takanishi and also Professor Sugano at that time were just students. And they sang the Waseda song quite impressively at Romansy. And now, of course, they are additional. Marc Raibert who was there. So yes, David Orin is now president elect of the Robotics and the Automation Society. So yeah, talking about people who were – and at that time, by the way 1983, I went for the first time in my life in China I spent one month in China at the Academia Sinica and then Zhejiang University. You can't imagine what was China in 1983. And then immediately from China I went to Japan also for the first time in my life. And I became a very, very good friend of Japan.

So in the following years most cases I was living outside my lab mostly in the U.S. I would say predominantly at Brown, Providence, and Philadelphia and also visiting and meeting MIT, Stanford, also Salt Lake City. The illustrious Steve Jacobsen team, he is a fantastic implementation in artificial arms and limbs and robots and CMU and Japan. So Japan I became very familiar with Tokyo, University of Tokyo, Waseda, Nagoya, all of Japan. I really became acquainted and very good friends and high estimator of Japanese, Professor Inoue and all of the people there at the University of Tokyo. And a great admirer of Japanese abilities. Professor Hirose. Really great names, great people, great scientists. Fantastic implementers of very complex systems, very creative. Sometimes even doing very strange things. So the very same idea of the human eye that was born at that time, more or less. And I was fascinated. Please remember that my background is biomedical engineer. It is coming back. Because I should say my main I will say revolutionary idea at that time was medical robotics. At that time, people did not believe in the possibility of using robots in the medicine. Well, of course, it was an idea, circulating, but many people were very skeptical.

At that time, the PUMA robot, the PUMA arm was there. I had the first PUMA arm in Italy. I was able to buy with my research funds and bring and use in the lab at that time, the first PUMA arm in Italy. So we were part of these efforts. But this was, I say, just on control, on very basic skills. But I thought that it was possible to integrate my competencies, not because of my competence because I thought for some application robotic could have been a fantastic solution. So merging and keeping into account my skills and my say knowledge of the medical problems with the new technology of robotics. So I began exploring. And this happened already in 1986, '87, I published a paper with a student of mine who is now a professor, Professor Massimo Bergamasco. At that time, we published the first paper on the IEEE transaction on biomedical engineering. It was a special issue on robotics. And we presented a finger to be used as a palpation device, you know, active sensing. Actually, the idea was to detect breast tumors or other pathologies essentially based on the ability to discriminate, embedded features with the different mechanical properties than the contiguous material.

And also at that time, I was the tutor of another brilliant student who became then also a specialist on hands and manipulation that is Antonio Bicchi. He is now a professor. I would say many of my students – Giorgio Buttazzo was another student of mine. We worked together. He spent a long training period at GRASP Lab, is now also a full professor. So during my career I have educated now maybe about 15 students who are full professors, in some cases associate professors in most of them – full professors in Italy and many abroad, including the U.S., one of them in Japan and one in Korea. So in Europe, different places.

Q: Are there any other ones you want to name specifically that come to mind?

Paolo Dario: I would hesitate otherwise I forget a few names. Well, in a way, my latest student is now director of our university. So Maria Chiara Carrozza she is also extremely good. She's an expert now on prosthetic hands, is a world expert in prosthetic hands and she's the director of my own university. And she was my Ph.D. student. So I think that it has been fun and also exciting to work together to create such a community.

Q: Have you had a lot of students that go into industry as well?

Paolo Dario: Yes, many of them. I'm very proud that this is another from let's say academic policy point of view, let's put this way. It was my vision. Traditionally, labs in the U.S. so in Japan, and in Europe are formed by one professor plus a few graduate students. This is a typical model.   In Japan, there is almost a rule that each laboratory that is named after a professor has twelve, thirteen people maximum. So a professor, maybe one associate professor, maybe one assistant or a post doc and then graduate and undergraduate students. I thought that this was – that I could explore a different frontier. And a different frontier is attracting, educating large numbers of students. I'm talking about graduate students. And this was very risky and also very controversial for some people. But I think this is, in fact, a very good model because one, you have a critical mass. You can do a big project. You can explore many different frontiers rather than being a specialist. I must say that many, many colleagues are now coming after this model and also increasing their laboratories. I was one of the first. I sure could not say the first, but certainly one of the pioneers of this new model in robotics that is large groups but not in research institutes but really in a university setting. And so it's a sort of pyramidal…

Q: You were talking about the large labs.

Paolo Dario: Yes. So I was able to create this – it was an adventure. It was a big risk. I like risk by the way. I like to take risk. I like to have visions and to go beyond the conventions in science, let's say here in engineering. I make mistakes sometimes but, in general, I'm able to adapt to circumstances and to find in any case a good solution for a problem. So this one having large laboratory was a risk. But I said, I believe that robotics needs a larger number of researchers, you know, to have an impact and my research activity is a demonstration of this. Essentially, I started – I mentioned this from one sensor to an array to the fingertip, then the finger, then the hand, then the entire limb, the shoulder, and more and complete systems. And in parallel, the number of people also grew. And the number of projects also grew. We were able to raise funds and when you raise large funds that were risky at the beginning. And we were ambitious. We were most of the first to investigate the European area.

So I said that I spent my eighties and also the beginning of nineties in Japan and in the U.S. mostly. And then I started to stay in Europe rather because of the growing of the European research program that I explored this since the very beginning. So large funds, we are talking about million euros, a $1 million, allowed me to pay, to support many students, many graduate students and many post docs. So it was a sort of, I would say, you know the more you take a risk and then you have resources and then you find the risks. And so I explored this model of many,

many Ph.D. students. Not one professor, one student, but one professor maybe ten students. And in the meantime a few post docs that could work as sort of quote trainees and trainers of this. And I would say this model works very nicely.

Q: So it was mostly your funding then from the European Commission.

Paolo Dario: At that time, yes.

Q: How has the changed over the years?

Paolo Dario: Still the large majority, with some exceptions, of course, there were peer – for example, still as I told you we had this big startup funding from Johnson & Johnson and Brown University. Then there was a period we were able to get quite substantial funds from the National Research Council of Italy. And this was the final big national program launched by Italy. And at that time I created a very strong and still lasting partnership with Giulio Sandini who also is a professor and director on one of the big groups at the Italian Institute of Technology working now on humanoid robot, robotics the iCub and so on. And we have many joint projects. We also playing the current venture for the new European flagship on robot companions that I'm coordinating and Giulio Sandini is a part of. And he's also a biomedical engineer as a professor.

And so we share this attention to the human model, to the biological models. So in that time, in the late eighties, early nineties, really I was quite young I was invited to be a member of the board of the Italian program, a big one on robotics. And in that framework we started two big projects. One on a robot, a system for hospitals. And the other one, as a robot for agriculture. I coordinated the project on the medical robot and Giulio Sandini the one on agriculture robotics. And we had a quite substantial amount of money. And we were able to test – I tested this model of coordinated project, how to work in a project – and this, in my opinion, is a very, very interesting model that is not common in the U.S. It's not common in Japan. I strongly believe in it value.

Of course, there are inefficiencies because when you have ten different groups of working on single subsystems and components, sometimes the efficiency is not the highest. But at the same time, you get the contributions from some of the leading groups in a country or in a continent. And it's really extremely I would say educational for all of us. And we were able to build – at that time we built a mobile robot, a big one with an arm. And the arm, by the way became, I'm also very proud to say the first product of the first startup company that I created in our laboratory. In 1991, we created the first startup company of the Scuola Superiore Sant'Anna, probably one of the first in Italy. They have now 50 employees, still alive and successful and building nice robots and nice mechanisms. This company, they have a number of Ph.D. graduates.

Q: What's the company?

Paolo Dario: It's interesting. The name is SM. That means Scienzia Machinale. Scienzia Machinale is an old Italian – it's not really Latin. It's an old Italian term to indicate mechanical science. It was proposed by Leonardo DaVinci. So we wanted to have – and the original signature, let's say brand, of Scienzia Machinale was written from right to left, as Leonardo wrote. So I think a very nice combination of say history, attention to our past and look for the future. This is typically Italian, I would say. And it's also our tradition, try to blend culture, interdisciplinary knowledge and what we hope is advanced engineering. So in 1991, this arm became the first product and all together, they represented one of the first robot in the world devoted to medical applications.

Q: Have you been involved in other startups, subsequently?

Paolo Dario: Yes. Right now, I'm the president of two startup companies, small but ready to grow. And our team has created more than 20 startup companies. So you asked me about our Ph.D. students if they work in industry, and my answer is yes, they work everywhere. They work in university in Italy and abroad. They work in research institutes. Some of them work in patent offices. Many of them work in industries. And many of them create or work in startup companies. So even if we produce many Ph.D. students, I must say that so far I don't have major complaints about finding jobs.   I would say it's a virtuous process, you know. Our institution has a high reputation. So just being here and being educated here like in the best university in the world it's a good passport. It's a good background for getting positions.

And I would say in addition there are, obviously the capabilities of those graduates. So I'm pretty happy about this model. So large number. So the ability to have an impact, not to miniaturize laboratory to do miniature things. But a large lab to do visible things or to miniaturize. But complex, I like this idea of adding an impact, okay, doing things that are visible and perceived at the frontier of science, but at the same time at the frontier of application. And we create jobs. We create people who have – who are successful, essentially. I am very glad that I'm not the only one, of course, but I'm glad that our students are highly appreciated worldwide. They go everywhere. They travel not like me. They travel not like me when I was their age, I mean. They are traveling all the time. They have a huge network of knowledge. So it's an interesting system that I'm quite proud of.

Q: Just to go back to some of the actual projects that you worked on, so your early work on the tactile sensors, what were some of the technical issues you were addressing at that time, and the real challenges you overcame? And what kind of materials and technology did you develop over time?

Paolo Dario: Yeah, well at that time, I would say the most challenging issues were, first of all, the understanding of the nature of touch in neurophysiology. This is really a challenge because while vision and motion so motor control and diseases related to motor control have been investigated quite a lot in neuroscience. So mapping of different areas of the brain for vision or for locomotion are quite well known like other reasoning, logic, language. Tactile sensing, touch, the sense of touch has been investigated at a much lower level of depth, I would say. So there was some knowledge about the main structure of skin and the different receptors and how they relate to cortical areas and then to other areas. But they were and still are not totally elucidated. So this one was one of the main challenges, and modeling the sense of touch in humans. And that was really fascinating. And this opened to me on the one hand a connection with the world, again, of biology, I was familiar with and very interested in, but also relation with neuroscientists. So we still are working very much with neuroscientists.

So in the last decade I was also one of the pioneers, I hope not to be too ambitious to say that, of neurorobotics, neurorobotics. It is really the fusion or the integration of knowledge in neuroscience and neurorobotics, okay? Also, this was very controversial. In the beginning people said, “Well, what is the relation?” or “the robot is just a machine.” So this idea of using robot to understand how biological systems work or using robots to – or robotic solution – to substitute, for example, limbs, you know, prosthetic, artificial. So the hand or the arm or a leg – it was, in my opinion, it was very, very important. So first point, neuro-scientific knowledge. Then the second issue was the technology for building tactile sensor. So at that time – we’re talking about twenty-five or more years ago – the technology was growing. It was still quite immature also. So together with my colleagues and my students I was able explore, also combine solutions. You know, working with piezoelectric materials, especially polymers that could adapt to and to conform different shapes, but also other solutions, like optical sensor – for example, optical fibers or thermistors or temperature sensors, and solid-state pressure sensors and the combination of.

You know, so the idea was to combine all these sensors, essentially into a layered structure. So this was probably one of the main innovation I was able to introduce. These are all the multilayered tactile sensor, not just one type, that is similar to what we have in our fingertip. So each sensor able to detect something. So high frequency vibrations – oh, sorry. I even used a nail, an artificial nail. So it was a combination of static or quasi-static sensing, dynamic sensing, temperature sensing. So at the end, one of the most – I’ll say this was really a pioneer work. Again, it was really cited by lot of people, some of them are now famous professor. At that time they were graduate students and they met me at that time. I already made many seminars and conferences on this. So it was a really quite pioneer work, was the idea of using a fingertip to detect texture or also the distribution of local stresses to detect sharp features, the ability to sense thermal flow from a heated finger to the object, to detect, to have a sense of the material – what the materials don't know. For example, when you touch wood or touch iron or steel, plastic, you have a different feeling even if the temperature is the same. And the reason is that heat is drawn at different speed by different materials for the same contact, more or less. And so you have different sensations on what you touch.

So this kind of thing that mixes technology with processing. So how this could be processed. And then, of course, also the activity – so how will you explore different surfaces? What is the strategy? Still now, we have project on that. So we made a lot of work on, for example, micro-technologies for increasing the resolution of the sensors or also silicon technologies and now hybrid technologies. So different kind of polymers. So we are collaborating with industry on this for detecting, for example, the hardness, softness, or, I would say, smoothness of the skin. So there is an interesting evolution of this.

Q: But in terms of the more signal processing and software side, what are the big challenges of integrating these different kinds of signals of the heat flow and of the texture?

Paolo Dario: Yeah, well, of course, there are different levels of integration of these. One level is the, let's say, the peripheral one. And this information can be either kept different, like in different sensory channels, okay, towards the brain, or this can be integrated at different levels because we have different levels of reactivity. Okay? So, for example, some of this information should be processed very quickly. In fact, some of these sensory information when we touch something that is really hot, so we need to react quickly. Sometimes this does not happen. In fact, when we touch something that is very hot, sometimes it takes time to remove the finger because it goes up to, let's say, deeper and more complex processing units. But maybe when you expect something, this, you are ready. You can close the loop much faster. And this is an example of some behavior. Then there are higher level, when you take maybe a decision or you define a strategy, and they go up to the, let's say, the cortical level – when you have a strategy, when you take a decisions.

So the sense of touch has, like other senses, of course, at many different levels of processing, some of them unconscious, some of them conscious, and the goal that we pursue is to try to integrate these different levels into an architecture that a robot can properly use. And I would say we are exploring all of these issues – also, gradually. At this time our – we still have the finger as a basic unit, you know, for exploring the sense of, for example, roughness. And my students, actually, my colleagues have now obtained very nice results published in top journals, including top neuroscience journals, because we are collaborating with neuroscientists now. We found finally some very good partners in neuroscience and these things. But then the next unit, let's say, some systems we are working on is the hand. So using this capability in order to control the grasping of the hand in robotics also in prosthesis. And then, finally, also we are using sense of touch for the foot now. We're also working on locomotion, this robot that actually has been developed after Waseda University. Here's an example of collaboration with Waseda University – has walking capabilities.

And walking is a very, very complex ability that, of course, humans have but we take quite a lot to learn it. And then the sense of touch, you can find the sense of touch in many other applications – from exoskeletons, for helping people, fragile elderly, but also disabled people to walk and we use contact sensors everywhere there is contact between, say, robotic devices and exoskeleton with the limbs. We use more and more robots for rehabilitation. We use – we have a new program that's very fascinating and very promising in using sensorized toys to detect pathologies of neurodevelopment in babies, actually, and children. We have developed a sort of gym, a sort of PlayStation, if you will, but for children, which children can play with their friends toys and while they play, the toys sense what the child is doing, if manipulation is physiological or has some pathological tract. And we can find touch even in micro-robots, small robots. So we are working on a new generation of robots for diagnostics or for therapy in which locomotion and vision and touch are also very important.

Q: Could you talk a little bit more about the significance of active touch and active sensing, how that changes the problem and where you came up with that?

Paolo Dario: Yeah, we started – you know, my very first development together with a student of contact sensing was a fixed platform on which we put objects, okay? And then the platform had many tactiles, many tactile units, and they could detect the presence or absence of these objects. This was a very preliminary and very primitive, if you will, technology for detecting an object using contact. But it was very, very clear very soon that this is not the solution – that we need activity to, how we say, to increase the information you can get. It's like when we observe something from different positions, essentially we increase the information that we get from an image. And for touch this is even more important. So by touching different object – so by the hand – we increase the information we can get and we can further increase this information by moving our cameras, let's say. Because the fingertip is a sort of camera, is a tactile camera. So it is like getting different kinds of information on an object from different points of view, actually. So active touch is fundamental, during desperation.

Then when you have learned what an object is, you just move with a very simple grasping. But it is very fascinating to explore this kind of active behavior and an ideal robot should be able to do that in the learning phase. The learning phase is probably the most fascinating phase in the development of a person, okay? Children always learn, but we always continue to learn. But it's fascinating how a newborn is learning and discovering the world. So active touch is like discovering the world and then when you have learned how that the object look like or feel like, you can use your mechanical – you can use the hand, because the hand is an exploratory tool, but then is also a very effective tool for doing things. So the two phases follow each other.

Q: So over the last thirty years of robotics we've seen commercial robots that have arms and hands and now they can walk and we're really just starting to see the beginning of robots with real touch. And what are the real challenges for consumer products that take advantage of this kind of touch?

Paolo Dario: See, this is the current challenge. And I would say that due to technology and due to progress in understanding of models on learning and perception lots of progress have been done in implementing complex and affective behaviors in robots. Still, this area is not reached the level that one would envisage and then one would really like to achieve in consumer, say, robots. So we are pursuing – or there are two main areas that are pursued. One is based on, let's say, the AI-style kind of approach that is developing a more and more effective algorithms to understand and to provide the robot with ability to discriminate, with ability to explore and manipulate, for example, objects. There is another route that can be pursued and that we are, for example, myself – I believe in this very much – that is the one based on the biological model. So understanding the brain, what are called the neurorobotics and there are models. And I would say now the majority, I dare to say, the majority of roboticists are working in this direction to – so to take as a model the structure of the human brain, so the different structures and to try to replicate – to understand and then replicate different levels of behavior starting from, now quite a lot, from low level animal species – so back to basics – in order to understand how these robots can become aware of the environment that they are. So to use touch in an active manner. To explore and then negotiate, let's say, environment that are not well known.

I would say that here there is a new area that is becoming extremely promising in my opinion. That is the field of embodied intelligence, okay. The area in embodied intelligence and people like Rolf Pfeifer at the University of Zurich have pioneered these areas recently. And then there are colleagues in my lab like Professor Cecilia Laschi who are exploring these fields very, very deeply. The idea is that body and brain cannot be separated. This is my opinion that the most attractive and promising approach in the last few years. So in the past the idea was that if you fabricate different components – I mentioned the tactile sensors and then the finger and then the hand and so on, and then the brain. Then you process these with some software. You can do things well. Like, the reality seems that this is not the right way to go. Of course, it works in many circumstances. But this is not how biological organisms really work. In biological organisms you cannot separate – actually, the function, the body structures and morphology, really, are developed, I'd say together with the processing.

And actually the processing, in some way, depends on the morphology with a very simple, basic behavior of neurons or group of neurons with different morphologies, you get different behaviors. So those features and imagines what we can call the connection, you know, the nexus of brain, body and mind even. You can come eventually to develop robots that could be as effective as biological systems. When I say biological systems I do not mean necessarily humans. Actually, it is probably more appropriate to start from basic, of course, trying to accelerate the evolution. But beginning from simple animals up to more complex animals. Some simple animals exhibit extraordinary performance and how they do is my own curiosity more and more and the curiosity of many colleagues. And it is not, how you say, admitting that we are not able to achieve complex behavior. It's just a parallel way, because we are still taking a lot of benefit from novel technology. We are – robotics has been able in the last few decades to develop extraordinary effective technologies. Okay. And to incorporate them into very reliable, very dependable machines.

We think of Mars or just an industrial robot or even the floor cleaning robots. They are extremely effective using available technology. So robotics, we are very optimistic, but we believe that in order to make the real next step that is obtaining behavior that could eventually allow to leave robots together with humans and then they can interact. We should probably pursue the other way. So, for example, developing what we call the "soft robots". "Soft" doesn't means necessarily sponge-like robots. It means soft behavior that is partly that is partly physical softness, but in part is a contra-softness. It's ability to adapt and to negotiate other shapes and machines and people. So this combination, those are the real frontiers. You know, given that we are already able to develop very effective components. So that the basic is mechatronics – incidentally, I should add that they've been one of the pioneers in Italy and also in Europe, Japanese have been the real pioneers – so mechatronics. Mechatronics is the real concept of fusion, not just the addition. But really the fusion of mechanical structures.

So you need the body of sensors, actuators, energy-- energy's very important. Energy will become one of the main issues in robotics. We cannot afford to have robots that consume, like, a heater, a boiler – energy like a boiler. We need a robot that – a very, very low consumption that means they have very smart solutions in them, then communication, architectures; all these integrated is mechatronics. So we know how to make mechatronic robot platform for robots. But next step is to go, as I say, beyond mechatronics. So rather than developing different components, putting together and then trying to miniaturize, we need to design entirely – you know, deeply integrated systems in which there is not distinction between what is mechanics, what they are – the actuators without the sensor. What is the intelligence, in a way? And this is how bodies in biology are built. And so I go back to my original passion: biomedical engineering.

Q: But it's really hard to design deeply integrated systems, isn't it? Why –

Paolo Dario: Absolutely. And it is a challenge, in fact. But I'm not saying that we should forget the other one. I'm saying that the mechatronic approach has been a major success of robotics, still is a major success and we should design robots according to the mechatronic approach if we want to develop machines that can be used by people now. But if you ask me what is the frontier of research? I would add to the previous one that is still there, this one of we call "sentient" machines. We call – actually, we are pursuing these in these new adventure that is the European initiative on FET flagship initiatives. You know, FET stands for "Future and Emerging Technology". Flagship is an initiative of size, one billion Euro, ten-year duration. President Obama just launched a sort of U.S. flagship in the U.S. – ten years also, similar size of funding. I would say more industry-related and application-related. The concept is co-something.

So co-worker – human-robot cooperation, which is perfectly fine. Okay? And this is more along the line of the mechatronics paradigm. Also, in Europe, we have initiatives in this field. I'm fully supporting and part of it. So how to increase and to improve the performance of the mechatronic platform plus the software? So intelligent machines. Robots are high performance, intelligent machines. But, in my opinion, the new research frontier – okay, entirely research frontier, or probably the most interesting for me and most challenging, as you said, is building new bodies and new brains for new robots. And so reducing or even eliminating this distinction between the different components, but building the system all together. So, of course, we can find the different morphologies and different organs in a body, but sometimes they are sort of indistinguishable. They work as a system. They really work together and this is, in my opinion, is a marvelous concept. Probably is the real new generation of machines. In the future one could use this concept to maybe for building cars or airplanes.

Q: Well, what do you think the major applications are gonna be for this new generation of robotics and mechatronics?

Paolo Dario: Well, our main field of application is taking care of humans. Okay? Because this soft behavior – one could call gentle behavior, you know – is like – but I don't want to use a word that can be misleading, but is like a pet. But sometimes you use the word pet, you have the impression of sort of low quality, low level. But from an interaction point of view, okay, how you – to develop the combination of mechanical properties, you don't want to have maybe a machine like this at home, you know? Of course, this is a fantastic piece of engineering. But it's also diverse. You know that if you touch this machine, it will be hard. So, of course, you can put something around, but in most cases the increasing behavior of a machine is something that you immediately distinguish from a living being. A living being is silent and is not noisy, is very, very sweet acting. The word is gracious. You know, I like this very much. Okay, this concept of graceful behavior. Actually, it was proposed or its importance was already mentioned by Steve Jacobsen almost thirty years ago. Because he developed the robot for Disney. And he had always this idea of graceful behavior. But he had in mind to make a robot for an amusement park, let's say, but actually this is really a fundamental feature.

You know, I can tell you my real dream is, in fact, I fought to put this concept in the flagship proposal. But it was – at this time it's in standby because it is considered to be frivolous. But my real dream is to develop a dancing partner robot. Because I think this would be the highest expression of performance, because a robot able to dance a passionate tango or a waltz or – it's a fantastic demonstration of performance. It's like having a Formula One. You know, the Formula One – the performance is handling and, above all, speed. But – so a robot is a different kind of performer and dancing – but not in a robotic way – in a totally human way, you know. I'm not able – I don't know if you are able, most of our listeners are really not, but they can easily recognize by carefully observing a human dancing nicely how difficult it is. The marvelous coordination of planning, of expression, of motion capabilities, coordination, and also emotional interaction with your partner. It's fantastic. And one could say – well, it is frivolous. It's not particularly useful. Yeah, my answer is a dancing robot, like Cinderella, could remove his or her dancing suit and maybe put on a working suit and be a waiter, be a worker plumber. Do a lot of different things because when you are able to develop this kind of performance, you are able to develop other useful one. But combining dream and usefulness is, my opinion, is a fantastic new frontier of robotics.

And, again, it is in my opinion – this is a really big issue – it is not possible to achieve this with, let's say, the traditional approach. There are lots of things that you can do with the traditional approach and I fully support. I'm fully involved <laughs> – I'm fully, I say, positive! But if you really want to develop a behavior like a very humble worm or a professional dancer, man or female, you need a different approach. And this is the one, in my opinion, robots should pursue.

Q: The idea of the robot team that can beat the World Cup champions.

Paolo Dario: Ah, but this is –

<overlapping conversation>

Paolo Dario: Yeah, but this is different kind of performance. Anyway, it's a strength. Okay? Of course, there is something coordination, but gracefulness. Okay? The football player is not particularly graceful. Well, one could say a gymnastic, a champion of gymnastic is also very highly coordinated, but dancing has an added value that is coordination with the partner. It is also communication, being – exchanging information. And this is my vision. Again, I'm saying that in order to do this we have the solution, as I said. Of course, it will take time. We want to develop new, entirely new materials, entirely new actuators, like muscles, new sensors, new energy, new communication, new nerves and fusing them together in the way I mentioned, using this science of embodiment. Not just screwing pieces together. This is the con. When you achieve – you are able to put together the system, I think one could develop a paradigm. Of course, it would take decades, but not so many. Actually, we are confident that if we start now working in this direction as we are doing and many others are doing, we can achieve this in a couple of decades, even earlier.

Q: Okay, before a couple of wrap-up questions, I just want to get one more historical question in, which is when you decided to come back to Italy after the States and Japan, what did robotics look like in Europe and in Italy and how has it evolved?

Paolo Dario: Yeah, it's an interesting point. I would say that robotics in Europe in the 90s was not as – definitely not as advanced as in Japan and as in the U.S. in the field of non-industrial robotics. You know, Europe was – maybe one could say leading, but certainly being one of the major players in industrial robotics. Okay? So the goal of Europe at that time was industrial robotics while in the U.S., and in Japan especially, the field of non-industrial robotics was explored very deeply and in a more advanced way. So this is why in the 90s I spent so much time with and in Japan and in the U.S. Okay? But then I started to introduce this concept – gradually, of course, with a lot of criticism, by the way, because Europeans are very pragmatic and many people say, "Well, this is not useful," the idea of service robots. Non-industrial, medical robots. And they gradually became very popular and accepted.

So now I dare to say that robotics in Europe is probably leading this area. I can't say why – maybe Korea is also working very much. But Korea is a relatively large but not so large country. You know, Europe is about five hundred million people. The U.S. is very, very good in military robotics now. The choice that the U.S. has done mostly were in the military field. Military field American robotics is at the top. Japan has declined, I must say. My Japanese friends will forgive me, but they've been very good in some areas, but not as visionary and as good as in the 90s. I think now Europe, essentially due to the major effort that have been invested, and I've been one of the players in the game, also, by convincing the commission – there are many, many names. Henrik Christensen, for example, have been leading person in this and now he's at Georgia Tech. He's doing the same in the U.S., by the way. But we created first the EURON network. Now it is called the EUROP. Still EURON is there, but we were able to gather so the European community of roboticists to convince the commission to make major investment, a few hundred million Euros, in this area. And so I think that to get now really Europe is at the top. It was not like this.

Q: And what's your advice for young people who are interested in pursuing a career in robotics or getting involved in robotics?

Paolo Dario: My advice is very simple, that is, first of all, to study a specific discipline to acquire a very basic competence in area like mechanical engineering, like computer science, like control and so on, because I think this is very important. Robotics, in my opinion, is for graduate students. It's not for undergraduate. It is – I have this opinion, that first you must dominate, be good in one discipline. But you should, if you want to become roboticist – the same is for biomedical engineering, by the way – you should not become a real specialist. Okay? On the contrary, after your basic studies that can be at the B.S., but better at Master level, rather than go narrow into a specialty, you must go wide in interdisciplinary. And these are really the difference. Robotics requires a broad vision, interest, curiosity and ability and will to learn different things rather than being specialized, to be non-specialized. <laughs> Okay? And to be able to deal with different things. To be curious physics, biology, basic science and material science, intelligence, even social and ethical, philosophy issues. You know, it should be this is really robotics, is a paradigm of – actually a paradigm of how intelligent systems, humans even, are. So and you can do this with – at the graduate level with working in a good group – in my opinion, a large group <laughs>, not a tiny group. But you can also follow and select very good advisor – there are so many robotics now – and learn under his or her guidance. But I think this is my recommendation.

So selecting one of the best robotics groups in the world and be part of the community. So be involved in large, international projects is very important. I say this, especially, you know because sometimes especially in the U.S. graduate students tend to remain in their own university for all their PhD period. This is wrong, in my opinion. I strongly recommend not to do this. Fortunately, in Europe we don't have this attitude. Actually, for example, it is compulsory to spend one year of your PhD abroad. Compulsory. Because this is very effective in learning, but also in opening your mind in understanding how things work in a different environment with different people. It's not only a matter of eating different food, learning different language. It's also this. But it's a matter of becoming acquainted with how different people, different areas maybe, work and this is very important to reach the skill that is needed to become a real leader in robotics. That is, as I said, in a way, robotics is against specialization. Okay? It is pro-very open mind. But it's fascinating. I would advise everybody to work in robotics.

Actually, many people advise us, because they recognize that robotics is so fascinating. Also, it is so attractive for ordinary people, for media. It is a way to have access to many different communities, because robotics can do everything. You can work with the rescue people. You can work with nurses and surgeons. You can work with artists. You can work with philosophers. You can work with neuroscientists who can get a Nobel Prize, with material scientists. You can publish together with them in journal – with thirty as an impact factor that will never be possible with traditional robotics. So it's expanding your mind, your reach, your culture, your networks. Like, my feeling, it's fantastic.

Q: Great. Is there anything you'd like to add or anything that we didn't cover?

Paolo Dario: No, I think it's – <laughs> what I wanted. There are many other things, but I think that's okay.

Q: Well, I guess the final question is Ducati or Moto Guzzi?

Paolo Dario: <laughs> No, I must admit that my motorcycle is a Suzuki V-Strom so it is an Enduro. But I had many Italian motorcycles. At the very beginning of my passion for it, which goes back to when I was sixteen. So I had Vespa scooter, a Piaggio. I had an Agusta MV – Agusta that was world champion for many years. I have a Moto Morini that is now – well, just the back was a fantastic motorcycle. And then Japanese, unfortunately, for my Italian pride, but very nice motorcycles. <laughs> I can say one final thing. You were talking about "sentient". Sentient is this sort of empathy between – that one would like to implement between a robot and a machine. Okay. A robot and the human. So, for example, the metaphor of the dancing partner robot is like this. You know, is how to create an empathy that is really moving together, having – no, looking eye to eye that is typically of a couple dancing. Of course, this is a dream, but it's a way.

But, actually, one could think about sentient with, like, a cat and the owner or a dog or a horse. And this kind of empathy. But I consider as an empathy or the relationship between myself and my motorbike. Of course, I have a wife, I have two daughters, I have many friends. <laughs> Real empathy is with them. But when I'm alone with my motorcycle there is an empathy. I talk to her and this demonstrates – and this doesn't happen with a car. It doesn't happen with a TV. <laughs> It happens with a motorcycle, with a bike. So you have this empathy. I really think that the same kind of empathy could become real with the robot companion, you know. That companion is not only assistant. It's an assistant in empathy. You know, it's some level of emotional interaction. But I want to say – I don't pretend that the machine is intelligent, has its own consciousness or – nothing like this because my background as a mechanical engineer <laughs> is such that I like the concept of a machine that has some degree of intelligence. Not as much as me, but the same level of empathy that I have with my motorcycle I think is very nice and fully affordable to all. This is what I like to achieve.

Q: Well, it's sort of an extension of yourself when it's –

Paolo Dario: Yeah, of course, exactly.

Q: – most effective. But I think the dance partner is even more complicated because not only are you empathizing with the partner but they're empathizing back with you. So there's double –

Paolo Dario: No, but, in fact, it's fascinating though.

Q: Yeah. Thank you very much.