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Vijay Kumar

An interview conducted by
Selma Šabanović
with
Peter Asaro

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Q: So where were you born and your early education?

Vijay Kumar: Okay. So I was born in India in a town called Patna, which is in Eastern India. And I spent most of my life in Central India and then in New Delhi and I went to school in Central India and then in New Delhi and then I did my Bachelor's degree at the Indian Institute of Technology in Kanpur, which is northeastern India. At 21 I decided to leave India and come to the United States for graduate education. And I did my doctorial degree in Ohio State University, where I finished it in 1987.

Q: What was your dissertation research on?

Vijay Kumar: I worked on trying to determine how to get legged vehicles to walk. And I spent quite a bit of time studying goats, horses, insects, and then trying to determine what kinds of gaits they employ, and how to take these gaits and translate them to robotic walking vehicles. And in Ohio State we had a big project where we a large group of people built a large walking vehicle, which weight about three thousand five hundred pounds and could carry about five hundred pound of payload. And one of the things I tried to determine was the exact sequence the leg should employ in order to walk in a stable fashion. And the other interesting question we had to answer is how to the load of the vehicle supported by six legs. In a car, that's done passively. You have four wheels that support the load of a car. But if you look at a horse, for example, it has four legs. It has the option to shift its weight. It also has the option to take the traction force and distribute it in an uneven way across its legs. So this vehicle had to the same kind of reasoning on the fly. And that's what I worked on.

Q: What was that called, the robot?

Vijay Kumar: So it was called the adapted suspension vehicle. And it was built in the nineteen eighties. And I believe it's in a museum somewhere in Columbus, Ohio now. But I was quite a monster.

Q: Who was your advisor?

Vijay Kumar: My advisor was Kenneth Waldron. Ken was a professor first at Houston, University of Houston, then at Ohio State. Then he moved to Stanford. And now he is at the University of Sydney in Australia.

Q: So, were there other people worked on the project with you?

Vijay Kumar: Yeah, it was a huge project. It was a five million dollar project and there were lots of people working on it, computer scientists, electrical engineers, and mechanical engineers.

Q: And just go a little way back. How did you decide to come to the US?

Vijay Kumar: Well. It was funny. I don't think I had a … you know… If I compare to kids these days they seem to have a five-year plan or ten-year plan. I mean for me, everything was I was just reacting to everything I saw and felt. It became clear that the kind of opportunities that were available after an undergraduate degree in India at that time were uninteresting. And so that's how I decided I needed to do graduate school. And then picking an area was also… again, there were some areas that were interesting and some that were not. I though robotics had the potential of retuning out to be something quite new. Back then, it was not an academic discipline. There were robots being used in the industry. So when I started doing a lot of interesting problems on could try to solve, if you look at a robot as an artificial but smart system, a human-like system, there were no such systems at that time. So I felt like there were just lots of opportunities and I wanted to work in this area. Of course I was a mechanical engineer. And as a mechanical engineer, the kinds of things that I was trained to think about at that time at least were every different. So I thought walking is something that was very mechanical in nature and I thought I should start with that.

Q: How did you become acquainted with robotics?

Vijay Kumar: How did I… sorry?

Q: How did you become familiar with robotics in the first place?

Vijay Kumar: Oh, I don't know. R2-D2 was my first robot. I mean that was the starting point. I don't know. I remember vaguely a satellite broadcast of a conference in the US that I just happened to listen to. Then I said this is something that I should think about more serious.

Q: What was your undergraduate degree?

Vijay Kumar: Mechanical Engineering. I was trained as a mechanical engineering. Yes.

Q: Were you interested in walking system at that time?

Vijay Kumar: No. It was… I applied to a whole bunch of schools. I remember looking options, looking at Cornell, looking at Ohio State. At Cornell I wound be doing turbulent fluid mechanics. At Ohio State I would be working on things connected to robotics. And I decided to go to Ohio State.

Q: And do you remember some of the people who work with you and Ken Waldron? You mentioned there were lots of people on this ASE project. So who were some of the other influential people that were part of that project?

Vijay Kumar: So there were obviously lots of friends, lots for colleges. I cannot say I drew a lot of inspiration from them. I think one another mentor I had There was another Australian by the name Ken Hunt, who is no longer with us. But I ended up with doing by Master's degree with him. And so he taught me a lot of very classical things in kinematics and geometry but looking at it from very modern perspective. And I think he is the first person who taught me to think scientifically and, you know, how to do rigorous analysis and research. So I think I owe a lot to him. I think if my plan was to continue with a Ph.D. at Ohio State, that may have been influenced by him. So I think he is the other person I would think a lot there at Ohio State. I also had a very good teacher Gary Kinzel, who is still at Ohio State. So he is someone else who influenced me tat that time.

Q: So was there other project that you worked on during your Ph.D.?

Vijay Kumar: They all had to do either with locomotion system and robotics, or kinematics. Again, kinematics, if you don't know, is the science of motion. So geometry is the science of shapes and forms. When shapes and forms move, that's called kinematics. So there were a lot of interesting things that emerges as a result of working kinematics. For instance, you know, a surprising result is no matter what algebraic curve you can draw on a piece of paper, you can always synthesis a mechanics device that can trace that curve. For circle, it is obvious. For a straight line… Actually straight line is not so obvious. So think about a mechanical linkage that you can design with pin joints and make that mechanical linkage track a straight line. That's a little tricky. But it turned out you can do it. But you also do a lot of complicated things. Not show how I got side tracked into these. But. So the projects I worked on were mostly in the area of kinematics and also in robotics.

Q: When you finish your Ph.D., how did you decide to go on after that?

Vijay Kumar: After my Ph.D., I knew I want to do research. And there were few opportunities in industry that excited me. Pretty soon I came to the conclusion that I want to do academia. And I looked around for programs in robotics. And there wasn't a whole lot back then in this area. I actually felt in love with Penn. At that point, Penn had a very influential roboticist, Richard Paul, who actually wrote the first book in robotics. Actually I should say in my second year here, Peter Corke was here working with Lou Paul. Richard Paul was called Lou Paul. There was also another fairly well known kinematician by the name Burton Paul. I remember joking that Penn is the only place with two Pauls with the first names that look like their last names. They are two names that are both first names, Rich Paul and Burton Paul. Also there was another person here at that time although I didn't know her until I joint, Ruzena Bajcsy. She turned out to be a quite influential person in terms of helping me think through what the interesting problems are what and kinds of research problems to attack. So she was also here at that time. So I like Penn a lot. And also Philadelphia is a great place to be. So I like that. So it's a combination of those things that attracted me to Penn.

Q: What year was that?

Vijay Kumar: 1987.

Q: You mentioned that there were a few opportunities in the industry but they were not necessarily very interesting to you. What were some of the industrial opportunities existed at that time?

Vijay Kumar: When I joint the academia, this was the time… Robotics had a lot of promise. A lot of industry started investing in robotics or research lab setup at that time. But they way they were going about installing robots turned out to be the wrong thing. So there was a boomier, the boomier of robotics maybe the early 80s and the late 70s and then there was a bust. Unfortunately, I was coming out right around the bust times. So the opportunities that were there were not really mainstream robotics opportunities. Some of them were in the defense and space industry. Because I was not a U.S. citizen, that posed a lot of problems. So I had opportunities at the AI labs in Schenectady for General Electric AI lab. I was looking at AT&T and I was looking at JPL. And somehow non of these opportunities were attractive or I elected not to purse them. But then when I wen to academia or when I went to an interview I found there were many universities were really interested in someone like me. And there were a lot of opportunities. And I knew at some point or the other I want to come back to academia to work with students to mentor, to train them. And I said, well, why not to start with this.

Q: What did you think was the thing that made the robotics industry in the early 80s not work out?

Vijay Kumar: Well, I think most of the American companies were thinking of robot as a way of replacing human workers. They had these visions of light-out factory where robots will just produce things. And it turned out that they grossly underestimated the difficulty in actually setting up an assembly line, setting up production lines. And they also did not pay careful attention to the role of a human worker. For instance, if you look at how Japanese did it, I think they pay a lot of attention to how the quality of the products could be improved, how space could be better utilized, and the spend less attention on how people could be replaced on robots. So the solutions they came up with were more holistic. And to this day I think Japan has had a better way of looking at robotics in manufacturing settings in the factory than the U.S. has. Because of that, I think industry started getting disenchanted with robotics. And I think some of that spread to the federal funding agencies. So pretty soon you couldn't write proposals with the word "robots" in it. So the National Science Foundation obviously was thinking beyond that. And it was thinking like most academics were. NSF had a longer vision. But Department of Defense was not particularly interested into this industry. So those were not good times.

Q: For how long the Department of Defense was not interested? Because now it's a very different playing field. <Laughs>

Vijay Kumar: Right. I know. I think it was not just the Department of Defense. I think if you were a professor from 1987 to 1995, you struggled a lot. I remember three or four year down when I was an assistant professor thinking that maybe this is the time to pack it in and try to look for something else. It was very hard to get funding. And if you don't have funding, you don't have students. If you don't have students you can't write papers. And it was tough going at first. But we came out of the recession then, the high interest rate era. And I think companies started investing in robotics again. The big auto manufactures went back into robotics. You know I hate to say this. Anytime we fight war, we look for new technology. Indirectly, disciplines like robotics benefit. That was part of it.

Q: When you first came the Penn, the GRASP lab was already alive. What was the program like as far as education of students in robotics?

Vijay Kumar: When I first came to Penn, GRASP lab was mostly a lab in the Computer Science Department. I was a mechanical engineering. I knew very little about computer science back then although I was very interested in it. And Ruzena Bajcsy was an individual kind of made me feel at home in a computer science setting. But it took a while for me to find my way. In fact the lab was actually extraordinarily small. It was in the basement in Moore Building. Actually she helped create this much bigger enterprise, which was across the street in 3401 in the 90s, and then subsequently moved here, where we are sitting. So I would say back then the lab was fairly one-dimensional in terms of the kinds of problems that it attacked, who was very computer science and information science centric. Which was good because for me that was one way of thinking that I had not gotten used to. It gave me lots of ideas. I think it taught me that you could really think about the problem of… So if I just back off, one big challenge you have at robot operating in the real world is they have to reason about the real world. And there are lots of mechanics in the real world. They have to interact with the real world. So anytime I pick up an object, it is a problem of mechanics. There is lots of mechanical engineering in there. So unless you understand the mechanics and unless you understand the interactions that occur, it's very hard to just think about writing, for example, control code or even code for perception. And all that is very fundamental to get robots to work. So it really made me sort of think harder of these problems. And till this day I think a lot of the things my students do is largely about creating software systems. But there is mechanics inside of all of those software models. And I think a lot of that really came about because of my exposer to fellow computer scientists in the GRASP laboratory.

Q: In those earlier, you mentioned that Ruzena made you feel comfortable as a mechanical engineer in computer science, or computer science lab. How did those interactions happen?

Vijay Kumar: Well, so Ruzena was interested in problems in perception, problems in artificial intelligence, and how you could actually solve some of these problems using robots. So very early on, she had this great idea, which is now called active perception, this idea that in order to perceive the world, you need to move. And so, when you need to move, there is motion involved. So there is mechanics in there, right? She was also interested in how you might explore environment. So if you pick up an object, you have them, you wave them around, you learn a little about the object. Again, this is perception, but the online problems are very mechanics oriented. And she was interested in how robots can cooperate. So early in my career at Penn, we started looking at the problem, actually with her, how do you get robots to cooperate, to pick up, for example, a piece of furniture and carry them. Well, unless you really understand the mechanics, unless you understand the control of the robots, and the interactions with the objects, it's very hard to solve these problems. So at a high level, she was interested in the same problem that I was interested in, except her methodologies were very different. She was trained as a computer scientist. She was an image understanding person. She was an AI person. And here I was coming more from the dynamics, from control side of things. So that's an example of this synergy. And, you know, we were often talking about the exact same things by in different languages. We learned each other's language and that helped.

Q: What was the first big project you undertook once you got to UPenn?

Vijay Kumar: I thing there were a lot of projects that I undertook. But the one big achievement in the late 80s and the early 90s was exactly the things I was talking about to you. We got robots to actually cooperate to carry objects. This may sound quite trivial. But if you just think about the problems these robots have to solve. Each one has, let's say, an arm. And it knows about its own arm's position and how its own arm is moving. But it doesn't know what the other arm is doing. So these robots have to sense each other through forces. And they have to coordinate motions. And again what these robots know is the overall task, which is to pick up this object and move it. So one very cool problem we solves is how do you get two robots to manipulate objects such as balls. I don't have a ball on my hand but you can imagine if I want to manipulate the ball, I not only have to move my arms, but I also have to let the ball roll along my palms. You have to model this and this is quite intrigue. The model is complex. And then try to figure out how you can get the robot to do what you want to do using information that the robot can sense, positions, forces at the palms, perhaps position of the ball as it contacts the palm. This is very tricky. So that was a big accomplishment in the early 90s.

Q: And how funded this research?

Vijay Kumar: This research is funded in part by a DARPA project that Ruzena was a PI on. And by that time I already got some funding from the National Science Foundation. Actually 91, that was sort of a turning point where I decided yes I want to stay in academia, where I was fortunate to win what is now called, actually I don't know what it's called now, but it was called the Presidential Young Investigator Award in 91. So that gave me enough funding to do the kinds of things I was interested in. That was kind of a turning point. But I was funded mostly by NSF and a little bit by DARPA, to answer your question.

Q: What's the next project you worked on?

Vijay Kumar: So I did a lot of things with again coordinating arms coordinating fingers. Working in the GRASP lab, I had to think about how robots grasp objects, you know, just joking. But we did… Again, the problems are very similar. I think one project that received a lot of notoriety is we were able to… Actually going back to by roots where we worked on walking vehicles. We developed initial prototypes of a walking chair for disabled people. So people with disabilities if you want to walk around, you are constrained by human made environments. And you really can't do things like a walk in a park, the park does not have a paved surface. And this is something we really worked very hard on. A group of very smart students who equipped conventional chairs with leg-like crutches and that could allow them to very over obstacles.

Q: And this is just the smart chair project or…?

Vijay Kumar: No.

Q: No. <Laughs> Ok.

Vijay Kumar: I think it was called the walking chair.

Q: Were there attempts to commercialize those?

Vijay Kumar: Yes. Actually there were some companies that came to us. I remembered Johnson & Johnson came and spent a day here. This was shortly before they decided they would put their eggs in the Dean Kamen basket. You know…, I forget the name of the…, you know the Segway like robot, that he developed. Anyway. So then they decided that was a safer bet. I think the world was not ready for the risk associated with embedded processors in devices you have to rely on. And wheel chair companies were quite risk-allergic. I mean, partially because they are regulated in a strange way because of the insurance industry. But partly because it's not an industry that… Even today, you don't see a lot of innovation. Wheel chairs are roughly what they were after the World War II. So there were attempts to commercialize them but none of these attempts really went very far.

Q: After the walking chair, what other kinds of projects were you interested in?

Vijay Kumar: After working on these walking chairs… So again, the common theme on all of these projects is that you have robots or subsystems of robots that need to cooperate. If you think about legs, the legs cooperate in order to walk the vehicle forward. If you think about grasping, you have the fingers that kinda cooperate to manipulate the object. Or arms that need to cooperate to pick up things. So in the 90s, mobile robots became very very popular. So we started to think about ways that mobile robots could collaborate on tasks. So we developed the first mobile manipulators, arms mounted on mobile robots. And we showed how they could cooperate. We also looked at how a team of mobile robots could solve problems that individual robots could not solve, for instance, problems in cooperatively exploring environments, cooperatively mapping environments. To this day, we have unsolved problems that we are still attacking with those kinds of robots. So that was in the late 90s and the early 21st century. And most recently we've been very interested in how we can actually take all of these to the 3rd dimension. So now we have teams of aerial robots doing much the same thing that ground robots were doing. And of course aerial robots are really game changers because they can do things from the top. Ground robots are either bolted to the floor or they are moving around on mobile basis. With aerial robots you can do a lot of things that you cannot do on ground robots. S
o we are interested in how you can have aerial robots cooperatively explore complex environments, how they can collaborate in picking up objects and manipulate them, how they can do assembly. A large part of my lab right now works on these kinds of problems.

Q: What are some of the principles in findings you based these robot collaboration on throughout the years?

Vijay Kumar: Are you asking if there is a unified theme through all of them?

Q: No. I am wondering of course your way of look at what collaboration among robots means in a different ways that you managed to have it implemented probably changed throughput the years. So I was wondering if you could tell us a little big more about the kind of science behind the movement - <Laughs>

Vijay Kumar: Yeah. I mean cooperation means lots of different interesting things to different interesting people. And the one thing that actually the common thread between all of the things that we do mostly has to really do with this underline, the online physical models that govern cooperation, especially when you collaboratively pick up an object, you collaboratively assemble things. But I think more importantly, the question in academia that you want to ask is, in addition to if this question is interesting or not, does it kind of land itself to academic research, does it land itself to training of doctorial students. That's something that Penn has a tradition of. We are committed to this. And personally, I am very committed to that. So I think that is one thing you have to look at. You have to take the overall problem, dissect it into smaller problems, and then go on to attack the smaller problems that land themselves to the writing of a doctorial thesis.

Q: What are some of the approaches that you used to develop collaboration of robots?

Vijay Kumar: I don't know that I could talk about a unified sway of doing this. But let me - At a higher level, let me try to articulate some of the design philosophies if you will. If you look at nature, where you have groups of natures collaborated to do tasks that individuals cannot. You will find several common features here. One is nature has solutions in which individual accomplish their little pieces in a completely decentralized way. So again if you and I pick up that table and walk out with it, I am not gonna be telling you what to do. Neither you gonna tell me what do to. I do my own thing. You do your own thing. But if we are truly cooperative, the thing that we want to do gets accomplished. It's even more obvious when you look at, for example, ants. We used to spend a lot of time studying ants. Ants cooperatively carry objects that are many many times their sizes. And again if you look at the actual data coming from ants, it's very clear that every ant is actually doing her own littler thing. But the own little thing that she does is so carefully designed. If everybody does the same thing, the task gets accomplished. So one of the goals in cooperation is to find out how to decomposed the big task into little subtasks. The other common thing about these solutions in nature, solutions we implemented in robots, is that each individual operates on local information. So again if you and I collaborate, I cannot possibly know all the things you know and you cannot possibly know all of the things I know. And oftentimes when carrying large objects, we don't even see each other. In fact I don't know what the object looks like from your side and you don't know what the object looks like from my side. So whatever solution you develop has to land itself to implementation using these very modest assumptions. I know what I know. You know what you know. And the question is what do we have to communicate in order to make sure that this task gets accomplished. And the third thing that is sort of a comment to of all of these is what we like to call anonymity. When we cooperate, the best way of cooperation is to assume that we are all anonymous. In other words, I make no special assumption about who I am cooperating with and the other way around. And again this is true in ants. Ants have very limited knowledge of who their neighbors are. They can identify neighbors, if the neighbors are there or not, but they don't now which neighbors are there. And you can argue it's because ants are homogenous. But actually that's not true. There is much heterogeneity in ants as there is in humans. But actually what the end result is if you assume homogeneity, the kinds of solutions that work are ones that are fairly robust. That's something else that we tried to realize in all our robots. And the side benefit of all of this is that if you assume homogeneity, the software I used for robot-X can also be used for robot-Y. And so this notion of anonymity helps. I used to joke when I first started working in robotics, to do a one robot experiment you needed one student, to do a two robot experiment you needed two students plus a third one that kept track of how the interactions are going. You can do the math. If you do a n-robots experiment, you need kind of need N squared students. If N is- If you don't have that much money you cannot do N-square experiments, or N-robots experiments. And biology again breaks this. It breaks this symmetry by saying, well, all you have to do is to figure out what one robot does and then just copy it for every one. So that was a big paradigm shift for us in how we though about robots software and robot mechanics in the same way.

Q: How did you start looking at things like ants or biological paradigms?

Vijay Kumar: I think this has been a theme in most robotics research. If you try to build intelligent systems, you try to look at proofs of concept that already exist. I think you will find that many people actually do this. Of course it is very hard for roboticists to go into the field and study animals. So oftentimes this works if you can strike up good collaborations. One of the people I work with is a professor in Arizona State, Stephen Pratt, who studies ants and ant behaviors. So with him, we've been looking at some very interesting problems. One is cooperative prey retrieval. Ants, there is this species of ants, when they find prey, they take the prey back to their nests as opposed to eating it right there. And oftentimes this prey is pretty big. So he did this initial experiment with a piece of fig that was about 20 times the size of an individual ant. And the ant sort of recruits other ants and they carry this thing back. So we got this idea that well maybe what we should do is to build artificial figs so that we can try to – the figs are - instrument these artificial figs so that you can actually study the behavior of individual ants. So we started working on this and we found that if you take a piece of plastic and if you smear fake juice on it, the ants will carry it. And then if you build the plastic to be deformable, the ants will actually stretch it or compress it as they move. If you take an object that is being carried by multiple that actually stretches and compresses, you get a pretty good idea of who is doing what. So that was the first instrument passively by looking at the stretching and compression, we are able to infer what ant is doing what. And we are also able to track all the ants. That was sort of our first study. That was kind of cool. With him, we are also learning how ants recruit each other and how they actually teach each other paths in the complex world, which is actually quite controversial this idea that a leader teaches a follower how to go from point A to point B, which ants supposedly do. So we are trying to verify it by creating little robot ants that teach real ants the wrong path and see if they continue to follow the wrong the path. There is a lot of interesting stuff that you can do if you look really at robotics and biology at a high level, we are both trying to answer the same questions. And there is a lot of synergy you can derive from each other by just sharing results and sharing methodologies.

Q: Are there other people that you've collaborated with over years?

Vijay Kumar: Yeah. So I have a collaboration – I have many collaborations here at Penn, molecular biologists, cell biologists, some of the behaviors employed by groups of molecules, groups of cells. Again, there've developed highly efficient mechanisms to, for example, sense hormones, how does a group of cells decide that the population of the cells is above a certain threshold and it's now time to do something else. In bacteria there is a phenomenon called persistence. They actually are robust to attacks from external agents like antibiotics for instance. So it turns out that there is a online behavior called the stringent response system that my colleague Harvey Rubin has told me all about it. We been sort of looking at how those kinds of behaviors can be realized in real robots systems to make them more robust and to make them more resistant to external threats. So there is those synergies. Most recently we are working on micro-robots that are actually powered by bacteria. On of the things that biology has but we've not exploited as roboticists is this amazing set of actuators. So bacteria have this flagellum that propels them through fairly remarkable speeds through fluids. The idea is if we take these bacteria, and we attach them to a robot, and we get them to swim the way we want, wow, we've got a robot. A small robot that can swim in the way we want. So we've been doing that in the lab. These is a lot of interesting collaborations we have right now with biologists here.

Q: Who were some other people you've collaborated with previously on other projects?

Vijay Kumar: I have too many of these. <Laughs>

Q: I mean some of the ones that kind of stick into your head as people you worked with a lot or you had very fruitful collaboration with.

Vijay Kumar: Yeah, certainly. I think Penn is a very collaborative place. A lot of colleagues here that we work with, our group works with. One other thing that's nice about Penn is we are very small. So if you are small, you don't have too many people doing the same thing. And if you don't have too many people doing the same thing, you talk to people who do different things. And that sparks really interesting collaborations. So we have an extraordinary controls group here. We have a great vision group here. So there is a lot of interesting collaborations there. We also, like I've said, have an excellent medical school and biologists who we collaborate with here. I can give you names of some of these people if that would interest you.

Q: Okay. Also, any students you've had who have moved on to be professors.

Vijay Kumar: Oh, I mean I have lots of students. How much time do we have? <Laughs> I have to say that's the one part of my job that I really enjoy, which is working with doctoral students. When you – we work hard at recruiting doctoral students and I just enjoy the process because you try to track the top people and they're like uncut stones and all you have to do is home them like until the stones become gems. And so this is a part that I enjoy a lot. I've had close to, I think I would say 30 PhD students and a good fraction of them are in academia themselves and several post-docs too, I think close to maybe 20, again many of them are in academia. And the reason I single out the ones that are in academia – actually I haven't singled them out, but I mention that is because I think they – I think I've transmitted my love for sort of supervising of the students to them and I think it's good that they're going on doing the same thing. So you asked who are – so just most recently I had – let's see, the last student to graduate was actually last week, Nora Ayanian, who is – she is still here. She is wrapping up her PhD student – PhD thesis, sorry, and she is looking at academic positions, postdoctoral opportunities. The one before that, Mahmut Selman Sakar is a postdoc at MIT. And then before that, Spring Berman, she is a postdoc at Harvard. I can go on and on. I can give you all kinds of names.

Q: What about the early ones from the '80s?

Vijay Kumar: So my very first PhD student, Nathan Ulrich, was probably the smartest mechanical designer that I ever had, very creative guy. He ended up doing a postdoc at Woods Hole Oceanographic Institute and then he ended up establishing his own company called Technique. So he really wanted to create new robots, build new robots and I think he continues to do work on novel devices at this company. Actually, he and his brother started this company that manufactured high-end scooters. This is when – when did scooters become a rage? Not – yeah, the push scooters, thank you I was looking for – so they produced what they called the Rolls Royce of scooters. So this was people like you and me. Actually, I have one at home. So really nice scooters made out of solid stuff, not this "Made in China" kind of production models. So they made those, they made electric bikes long before electric bikes were a big thing. Now, of course, you go to Shanghai and any snapshot you take will have seven or ten electric bikes in it. So he continues to do these kinds of things, creating novel products and bringing them to market.

Q: Where is that company?

Vijay Kumar: It's based in Boston, actually I don't exactly know where but he is in the Massachusetts area.

Q: Some of your work, has it gone towards particular applications?

Vijay Kumar: Well, I mean when you do research obviously you want to be aware of applications and be guided by them but it's a little dangerous to be obsessed about applications so we try not to do that. I mean, ultimately, the work that you do even though it's an engineering thesis has to stand on its own. So no we don't particularly think about real applications. Although, I have to say most recently the project I'm most excited about is one that is really motivated by applications. So I'm sure you're all aware of the tragedy in Fukushima and it's ironic that the tragedy happened in Japan, a country which is known for its robotics work and yet there was very little that the experts could do. And there are many reasons for that. So one of the things we're really interested in doing is to bring aerial robots and apply them to this setting. And we also want to think about autonomy. So one of the difficulties in these kinds of settings is you cannot teleoperate these robots. You're not allowed to come close to the actual reactor building because of radiation – dangers of radiation. Second, even if you come reasonably close, the communications link is greatly impaired because of electromagnetic radiation. So what that really means is you want a robot that goes autonomously, gathers data, comes back to you and reports. Well, it may not come back to you, chances are that robot is lost forever, but it has the data, gives you the data and then it dies. So we're trying to explore this paradigm in the setting of buildings in the Fukushima area. We're going to start with Sendai this summer, send our robots to some of these collapsed buildings. And so here's a project where we want to solve this problem, we want to attack this application area and we think there could be obvious benefits here. So we're doing that. But, in general, we try not to do things like this.

Q: Do you work with any Japanese collaborators on that?

Vijay Kumar: Yes. So we've just started this collaboration. We have a pile of grant from NSF to go visit Tohoku University in Sendai and we're going to perform some preliminary experiments this summer.

Q: So besides your own work, we talked a little bit in the beginning about the GRASP lab and you've also directed the lab for an extended time, so we were wondering if you could tell us a little bit about the development of the lab, what it was like when you got there? Why don't you mention a bit what it was like when you took over the directorship and how it's developed through the years. Robotics as a program at Pennsylvania.

Vijay Kumar: Yeah, sure. I mean I think when Ruzena was there, she really had the vision to set up the lab. She also acquired, some really good space for us and helped nurture the lab during its early years. But when she left, there was a big leadership vacuum and that was pretty challenging to sort of step in, and as I said, they were mostly computer scientists and I was a lone non-computer scientist yet running a lab which really was part of the computer science department. I mean that's not to say that my colleagues made me feel welcomed but still it was a challenge. I think the one big change during my tenure as the director was to take the lab and to bring in more participation from other departments. We recruited some top-notch electrical engineering professors. And so right now you look at the lab, whether you look at faculty or students or postdocs, it's roughly one-third mechanical engineering, one-third computer science, one-third electrical engineering. And really, that reflects the true nature of the discipline. So I would say that it shifted the overall research, if you looked at the lab, it moved more from the perception centric programs – research programs that Ruzena was more interested in and obviously she was the person in the world in that area to, I think, more broad-based programs which brought in control, coordination, communication, design and I think that was a big shift.

Q: How did you come to be the director?

Vijay Kumar: <Laughs> I don't know.

Q: <inaudible> how does this process happen?

Vijay Kumar: Suddenly – I think it may well have been that – I mean I was pretty junior at that time but I was the next most senior person after Ruzena and I guess it fell into my lap.

Q: Do you have any favorite stories from the lab or its development?

Vijay Kumar: You know, the one thing that I remember is that – so from my really early days I remember that I used to come in on Sundays. Ruzena was there on Sundays and all her students were there on Sunday. And they would all have their weekly meetings with her on Sunday. And if she was there they were all there. It was just amazing and I've never seen this culture elsewhere. That was the one thing that I could not sustain <laughs> mostly because of me, once I had a family and so it's hard to do. But that didn't happen so that was somewhat funny. The other thing that was actually – she had this T-shirt, this sweatshirt which had the word "results" printed on the back and that's how she wanted – I want results and she would turn her back and walk away to her students, that was funny. But those <crosstalk> Yeah. And I still tell my students this so they say, "Well I can take this time off?" And I said, "I don't care as long as you deliver the results." And that's what it should be about, right?

Q: How do you see the strengths and aims of the robotics program at Penn relative to some of the other robotics programs at MIT or Carnegie Mellon?

Vijay Kumar: So – yeah I think there are many outstanding programs. I would say we're among the top five if not the top three. I think in terms of size, I think Carnegie Mellon is the big outlier, they're about, I would say, 10 times our size. But I think in terms of – I think they have a culture of going after big projects, like Grant Challenge for example, while we probably don't. I think we pay a lot more – we're probably a lot more academic in nature. I think we spend a lot more time thinking about doctoral education, not to say they don't, but I think that's one big difference. MIT's great. Much of MIT's program is anchored in the artificial intelligence laboratory. It's sort of computer science and artificial intelligence. So I think that's the difference. I think this is sort of unique in the sense that it is common space that's shared by three different departments. And to this day, you walk into the lab and you have no idea which space belongs to who and to what department. You walk into the lab you'll see lots of students and I guarantee you will not be able to identify who's a mechanical engineer, who's an electric engineer, who's a computer scientist and I think that's very unique of Penn. We're also incredibly collaborative. I think it's – I'm really amazed by how students write papers together and often times the advisors don't even know that they're collaborating with other students and that's great. So I think that culture is part of who we are.

Q: How do you think robotics, just particularly the fields that you've been interested in, have changed through the years and what are some of the future challenges?

Vijay Kumar: Let's see, if you look at cooperative robotics, I think one thing that has happened over the years – so robotics, like many other sciences I think has been greatly influenced by technological advances. So I think the biggest technological advance obviously is processing, right? You know about Moore's law and all those things. I remember when I was a doctoral student and when we were implementing code we actually had to worry about the number of adds and multiplies in our code to make sure that we weren't overloading the processor. Again, to put things in perspective, back then a program with 8086 Intel Processors, if you don't know what that is you have to go back from a Pentium before that came a 486, 386, 286, and then an 86 so it was that long ago. And so now you don't have to worry about that. In some sense I think we're spoiled by the largest but in another sense I think it's allowed us to dream and do things that we would have thought to be completely infeasible back then. I think the other technological change that has happened is I think if you look at the price to performance ratio of sensors that's fallen dramatically. So we now have a lot more data than we could have hoped for. And, again, that has influenced how you think about problems. I think the third thing that I would say is that in going back we just did not have a critical mass of roboticists creating robots. Now, it's relatively easy. If I want to make a particular robot with some sort of specification, unique specification, for a particular task it's not a big deal, I can do it. Or if I'm too lazy or if I don't want to spend my energy do it, I can go buy it. That was not the case before, right?

So when you think about the work that we do here – so for example, one of my most successful students, Nathan Michael who is now a research assistant professor here, he decided that he wanted to build his own robots and he took a combination of off-the-shelf parts and fabricated other parts and he built his own multi-robot system. I mean not to take away from his creativity and his novel designs but this was much harder to do a while back. So I think these technological changes have influenced the way we think about problems and the problems we think about solving.

Q: So what are some of the new problems they can now think about solving that you wouldn't have thought about before?

Vijay Kumar: Right, so, for instance, now we're thinking about deploying tens of robots in a building – in this engineering complex. So for instance, last year we – so I told you about Nathan, he was involved in this, too. We did an experiment where we had – we told the robot to go not just into the next building but the building adjacent to that and to a corner of that building and to get there and tell us what was happening. And so this robot was able to recruit other robots that acted as relays and they set up their own wireless ad-hoc network. And so I'm sitting here and I could actually in principle observe what was going on in a corner of the town building. So you need lots of robots to do things like this. And, again, often times we don't attack these kinds of problems unless we know that these problems are doable in the real world. So that's an example of something we would not have attempted 10 years ago.

Q: What do you think are some of the coming challenges in robotics or some of the coming new problems?

Vijay Kumar: I think one huge change I think is our ability to really develop three-dimensional autonomous flying robots. The UAV industry is huge mostly because of these big drone aircrafts that fly at really high altitudes and do bad things that I don't care about. But I think – and they're very expensive. But I think the time has sort of come that you can take those big objects and scale them down to really small objects and then make them completely autonomous. So if you do that, I think the third dimension adds so much to robotics and if you look at the number of aerial robot sessions and conferences, it's exploding. I think – so that's a big change in the next four to five years that we'll see coming.

Q: What do you see is the social or societal role of robotics if any?

Vijay Kumar: You mean what role society has to play or the other way around?

Q: Both, if you could answer both that would be great.

Vijay Kumar: So I think the one thing – so you may or may not know about this but there's a new robotics initiative that we're helping push through Washington and we hope they'll be funding for all kinds of new interesting projects both in academia and also in industry. So this is called robotics 2.0. So, as opposed to 1.0, 2.0 now acknowledges and emphasizes the role that humans play in a robotic society or the other way around, robots play in a human society. And so the increasing – the realization is that no matter what the application you want humans and robotics to work together and I think that is going to – you're going to see more and more of that. Already it happens in – for example in the operating theatre where surgical robots are operated by surgeons and there's things happening together. I think it happens a little bit in factories where you have humans working next to robots and in the kinds of missions that I was talking about in Fukushima. It's hard for humans to do it alone so they'll need robots. On the other hand, robots will need to compliment humans and I think that that is going to – you're going to see more and more of that. And right now the only robot we have in our homes are vacuum cleaning robots partially because of economics, partially because of what society is willing to accept. But I think you'll see a lot more of these kinds of robots in homes and I think it'll bridge the gap between humans and robots and I think you'll see a lot more of robots everywhere.

Q: The question that we usually finish with is could you give some advice to young people who are interested in robotics?

Vijay Kumar: <Laughs> How young are these people that you are…

Q: It can be any age that you think. Of course now it's from "K to whatever."

Vijay Kumar: Well okay. So here's my – so from the standpoint of education, I think I often call robotics the canonical engineering discipline. And the reason is it's A) it's synthetic. Unlike many engineering disciplines where you analyze things, here the whole goal of robotics is to build things. And it forces you to learn the signs that you need to build these things. So if I were to restructure engineering programs, I would simply have the very first course be a robotics course and from that build engineering science courses that could help students build better robots. So this is sort of a top-down way of doing robotics. But getting off that soapbox, I would tell students that this is a good way to learn a wide variety of techniques that are used in engineering. Well today, robotics doesn't include biology as much as it could so bioengineering and biomedical engineering is not really a central part of robotics but that's just a question of time. I mean that will also creep in. Likewise, it may not include chemical engineering or material signs, but I think again it's a question of time. We're going to be looking for novel materials. And so it's really the best way to learn about engineering. So if you're interested in creating anything in an engineering-type setting, building physical devices, robotics is the discipline to get interested in. I would also say it really has a truly transformational ability here or potential here. So if you look at – so the U.S. is not yet doing this but if you look at, for example, Japan, Korea, Europe, many countries in Europe, in a handful of – if you were to single out a handful of technologies that they're sort of emphasizing, robotics is one of them. I think we're a little behind the curve, but I would tell people this is where the action is and this is where you need to be.

Q: Why do you think the U.S. is behind the curve?

Vijay Kumar: I think we are a lot more careful about adopting new top-down initiatives. I think we're a lot more free spirited and I think that's good, that's why I think we attract the best talent. But if robotics were a social movement then I think everybody would buy into it in a heartbeat. But I just got off my soapbox but when I was on my soapbox I'm preaching to you and you're not going to accept that, right? You've got to believe it. So I think today that kids are believing it. I mean you see – we run the first Lego League competition at Penn and I was the head of all judges. So I'm looking at these third graders, these fourth graders, these fifth graders and they're trying to explain to me the basics of control as they see it in the robots and you know that we're connecting with them indirectly. So I think this is really the discipline to be in that sense and so I think it's a question of time before we buy into it at the level of Washington and below. And the new robotics 2.0 initiative hopefully will reinforce that.

Q: Thank you.

Vijay Kumar: Did that help?

Q: Thank you so much. Yes, no, that's great.