Arroyo Grande, CA
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George Bekey

An interview conducted by
Peter Asaro

11/12/2010

Q: So why don't we start by just having you tell us where you were born and where you grew up.

George Bekey: I was born in Slovakia, in the City of Bratislava, which is the capital. Our family immigrated just at the beginning of the Second World War and by then it was impossible to get the visas to the United States because United States had nationality quotas in those days, from each country. So we went to South America and lived in Bolivia for five years waiting for our number to come up, and when it came up we moved to Los Angeles.

Q: And how old were you then?

George Bekey: When we got here I was 17.

Q: You did your undergraduate at UCLA?

George Bekey: I did my undergraduate work at UCLA, except for the senior year, which I did at Berkeley. UCLA was just starting its engineering curriculum when I went there. Basically they added one year every year so when I became a senior I could've stayed at UCLA, it was the first time they offered a senior year, but I was also eager to get away from home and so I really wanted to go to a more established place and not be a guinea pig in the first year so I went to Berkley and had a wonderful year.

Q: You wanted to be an engineer.

George Bekey: Yes, and my father was an engineer, and I guess it was largely inspiration from him and I was good at mathematics and so I've always wanted to be an engineer, but that's not completely true. Once I got my masters in engineering, I went through a period when I seriously considered becoming a minister, and I actually I was working running a computer at UCLA and in the afternoons I came to USC, which at that time had an accredited theological seminary on the campus. So I came here, I spent 2 1/2 years, almost 3 years in a master of theology program and the first year were undergraduate deficiencies that I had because engineers have almost no humanities and social sciences. So I spent the first year taking Sociology 101, Psychology 101, and so on. The second year I took all the things that I wanted. In the third year, second and third year, by the fourth year it would've been entirely professional courses like in running a church, and I couldn't stand it so I dropped out.

Q: Were you studying robotics from the beginning or when did your interest in robotics…?

George Bekey: No, my interest in robotics started in the 1980s. I was at USC, of course, where I started in 1962, so I was at USC 40 years before I formally retired and came here to Cal Poly where I now have a faculty position. In the 1980s we hired a young man from Stanford who was the first robotics person in the School of Engineering at USC.

Q: And who was that?

George Bekey: Why am I drawing a blank on his name? It'll come to me in a moment. You'll be doing editing anyway, right?

Q: Yeah.

George Bekey: So as soon as I get the name I'll tell you. He dropped out of robotics by the way, sometime after that, but he got his PhD at Stanford and when he came he really wanted to have a robot manipulator. When he came in the 1980s we really had no mobile robots yet, except a few remotely guided vehicles on factory floors, but largely it was manipulators. So I wrote a grant proposal to NSF and got money to buy a Puma manipulator and so that came and then he and I started a robotics lab. It was only in the 1990s when I had a number of students working in the lab with me and we began to get interested in mobile robots and then we built 4-legged and 6-legged and wheeled machines that ran around and we also got interested in robot helicopters because the tradition that Gaurav Sukhatme followed and took on for me and continued in the process.

Q: I saw one of those helicopters.

George Bekey: Good. There's a picture on that wall that shows some of my students and some of the various assorted robots that we built.

Q: We'll have to get a shot of that.

George Bekey: Yeah.

Q: So what were you doing for the 20 years from when you started on the faculty until you started working in robotics?

George Bekey: I wrote my thesis on mathematical models of human operators in control systems. It was how do you represent a pilot, for example, flying by instruments? What is the mathematical relationship between the visual input and the manual output in controlling a joystick, let's say? And then I continued in that kind of work for a number of years, maybe 6, 8, 10 years after I came to USC, but I was also very interested in biomedical engineering, and this started because I met one of the people on my PhD committee at UCLA had called me in one day and said, "George, you're the one with the most peculiar interests among the students I know here. There's a man at the medical school who needs some advice from an engineer because he says he's getting very strange results. He says he's got blood flowing against the pressure gradient in the sheep that he works with. It's flowing uphill and he doesn't understand it." And he said, "I'm not interested, can you go see him?" So I went to see him. So I went to see Professor Assali, A-S-S-A-L-I, who was in physiology and obstetrics at the UCLA Medical School. It turned out that the reason for the mysterious uphill flow was that he didn't understand that this is a dynamic phenomenon and not a static one and so when blood is ejected by the heart it has inertia. Each bolus of blood, you might say, has inertia, so that even when the pressure stops and the pressure gradient reverses, the blood continues to flow against the pressure gradient but with decreasing velocity. Does that make sense?

Q: Yeah.

George Bekey: So that's what it was and then we began to build mathematical models of this process and I worked with Dr. Assali for maybe 5 or 6 years, then I started the Biomedical Engineering Department at USC and did a number of other things involving respiration, circulation, muscle function and so on.

Q: What year was the department founded?

George Bekey: Probably in the early '70s. I would have to look it up because I don't remember but that's approximately right. So I started in human operator models, then at the same time as I moved into biomedical engineering things, I also started to get interested in signal processing and in introduced the first course in digital signal processing at USC which is kind of amazing because when I left my undergraduate years I actually had been consulting for Beckman Instruments and working on analog computers. Now most people don't remember what an analog computer is like but in those days that's what I did and so some time in the 1960s I co-authored a book, this green book right here, hypercomputation refers to a combined analog and digital computation. So the idea was to be able to get the speed and bandwidth out of the analog computer and the precision out of the digital computer. And I think the copyright date is 1968. So, as you can see, I did a variety of things. Then in the 1980s, it was interesting, because as I started learning about robotics what I discovered was that in some ways the field of robotics was a blend of many of the things I had studied before. Certainly the robot was, in some sense, modeled after a human, so that what I learned about manipulation in manual control systems was also applicable, to a large extent, here. There was a great deal of signal processing, there was a lot of control, of course I was a controls person. So many of these things fitted very well and they began to click and come together. So then as I got into robotics I stayed in the field, and I'm still there.

Q: So who was your thesis advisor?

George Bekey: My thesis advisor at UCLA was John Lyman whose field was biotechnology. They didn't call it biomedical engineering. He was really more interested in human factors, the ways in which humans relate to machines and operate machines, and this whole idea of human operator models came out of my PhD thesis. He has since died.

Q: Yeah, what kind of influence did cybernetics have on that field?

George Bekey: Well quite a bit. I was personally very influenced by it, meeting Norbert Wiener who invented that word, as far as I know, and particularly I've had, from the very beginning of my college career, I've been very interested in the broader impacts of science and technology so Wiener's book on *The Human Use of Human Beings* was one that had a great deal of influence on me. I always felt that we really needed to make sure that human beings are not treated like machines or become machines and this clearly had a lot of effect on my studies in robotics as well. I think in a curious way I've always had the feeling that as you study robots and the way in which particularly humanoid robots, particularly the way in which they behave, we also learn something about ourselves, and that gives you, in one sentence, some of my philosophy of life.

Q: So what are some of the things you've learned about people by studying robots?

George Bekey: It's particularly the things where robots and people are different, makes you appreciate the way in which we as humans process information, the way in which we're able to do multitasking in ways in which robots can't do very well. We certainly slow ourselves down by multitasking, but that doesn't mean that we can't do it. As you know, this is one of the curses of the present time is that everybody wants to do multitasking. So that's one of the issues. And I'm enormously impressed by the human sensory system. We have an amazing way of receiving information from multiple senses simultaneously, and then assigning weights to these so at times vision is more important than hearing, and other times hearing is more important than other times. The sense of smell dominates everything if you smell smoke, and so on. So these kinds of subtle changes in the way we relate to the world are very important in robotics, because after all a robot is a machine that senses the world, and so sensing is very important but senses for robots tend to be uni-functional. They don't have the ability to do that kind of blending, but I think it'll happen more and more.

Q: Fusion.

George Bekey: That's right, sensor fusion I think which humans do all the time, and it's becoming more and more important in robotics as well.

Q: So what are some of the central problems that you've focused on in your robotics career?

George Bekey: Well I was particularly interested in ways in which robots can learn and display some intelligence. So in the early days, as you know, we spent so much time just keeping them working that mean time between failures wasn't very long and also in the early days we just couldn't buy inexpensive robots to use in the lab. So when I built the robotics lab at USC I actually put in a small machine shop. So we had a lathe and a drill press and things like that so that my students actually made parts that were needed to put robots together, and this was unheard of in a computer science department. You probably know, there's a famous saying, never trust a computer scientist who carries a screwdriver. So we did a lot more than screwdrivers. So initially our goal was to try to do things about locomotion. Actually Tony Lewis worked on one of the projects having to do with enabling robots to learn how to walk. We built several 6-legged machines, and I think he carried on some of this work at Iguana Robotics as well. So we built these machines where we did not specifically program a movement sequence for the legs, and so when you first turned it on and it had some kind of a reward system to see how far it could travel in the direction of the body axis, and of course it does nothing but fall down and its legs flail wildly, but little by little the machine learns how to select the leg sequence that gives it mobility forward, and so our robots learned how to do a wave gait so that they used the two front legs, the two middle legs and two rear legs in sequence in a way that travels across the body, and so on. So that was one of the issues, then I had a contract from JPL which involved comparing wheeled and legged robots on a simulated moon-like surface. So we built a sandbox with sand that followed JPL specifications as being something equivalent to moon sand, and we put in rocks and whatever.

Q: Sand isn't particularly good for robots.

George Bekey: Yeah, and we found that legged robots actually do better than wheeled robots if there are a lot of obstacles that they have to climb over. Otherwise they're much slower and use a lot more energy than wheeled robots.

Q: What was the first robot that you worked on?

George Bekey: I don't remember. Well the first robot was a Puma, of course. The first robot we worked on in the lab was the robot manipulator and then because of the interest I had had in manipulation in manual control, one of the things that we wanted to do is to see whether we could get robot arms to pick up objects and manipulate them. So this led to collaboration with a man named Tomovich from the former Yugoslavia who had been the developer of probably the first five fingered hand for robots. Actually he originally developed it as a prosthetic device, and then we adapted it to become a robot hand and having five fingers, which were not independently controlled, but were synergistically controlled, so what happened was if the hand reached any kind of an object, then the fingers would all begin to close until they made contact. So it just meant that it was passively shape adaptive. It could pick up an object of any arbitrary shape without having to be individually commanded for each finger. So this got us into some work on robot hands that we did for maybe 10 years or so.

Q: What were the biggest challenges in grasp and manipulation?

George Bekey: I would say from my point of view one of the biggest challenges was just simply mechanical reliability. We had a lot of trouble with these hands. We installed pressure sensors on the sensitive surfaces of the fingers and palm so that worked pretty well, but you see the whole goal was to try to build a very simple and inexpensive hand to compete with the usual parallel jaw grippers that were used in industry. And when we could keep the hand working it worked very well. But I never was able to find, to be honest with you, the killer application for a multi-fingered robot hand, as a robot hand. Ideally it would be excellent for a prosthetic hand, but for a prosthetic hand now one needed nearly total reliability. For the robotic hand the applications that we tried which were primarily having to do with manufacturing, the idea being that since the human hand is highly adaptive and can pick up objects of a variety of shapes and sizes, the robot hand should be able to do the same. And the answer is yes, it could, however to build a 5-fingered, reliable hand is very expensive, and it was much cheaper for industry for the robot arm to go and pick up a different hand from some magazine of hands then you could get one that would be designed to pick up small round objects, or fat square objects, and so on. And that was a lot less expensive to have a series of special purpose grippers, but nevertheless, we did what professors do, we published a lot of papers on grasping.

Q: Are you still involved in the field of grasping?

George Bekey: Not anymore really. Last year I was invited to give a talk on the history of grasping, but I don't have anything to do with it anymore.

Q: And did you build other hands after that hand?

George Bekey: No, that was really the only hand that we built. I still have one, the latest model, in a file cabinet in my office at USC, and it comes out occasionally for historical reasons.

Q: What was the first mobile robot that you worked on?

George Bekey: Well we built two or three of them and I'm trying to remember which one was the first one.

Q: You can just tell me about all of them.

George Bekey: The first mobile robot that I worked on was actually done jointly with Bob McGhee who joined E. faculty at USC about the same time I did, he had just graduated, and we had a PhD student named Andrew Frank, Andy's now in the faculty at UC Davis, but he had the marvelous combination of having had a bachelor's degree in mechanical engineering so he really understood mechanical things, and so in the 1960s we built the first 4-legged walking machine in North America, to the best of our knowledge, and it was mechanical and slow, but it did walk and it walked with a variety of gaits, slowly, and it could do the equivalent gait of a trot for example. We called it a horse, but of course it didn't really look like a horse, but more or less, it had longer legs. That green book has a picture of it. If you look in the index under Phony Pony, you'll find it.

Q: Phony Pony was the name of it?

George Bekey: The Phony Pony was the name of it. It shows up in other people's robotics books.

Q: What year was that?

George Bekey: I'm guessing '68, '69.

<silence>

George Bekey: Not there?

Q: Not in the index.

George Bekey: I'll show it to you.

Q: This was before you really got into robotics?

George Bekey: I have a video of this thing walking.

Q: So you didn't get into robotics until the '80s?

George Bekey: Well that's really not true. I sort of repressed this idea, because this really was a robot, but then we didn't do anything for 20 years.

Q: You considered this robotics at the time or did you consider this just a control application, or?

George Bekey: Well I wasn't using the word robotics. I don't think we did.

Q: What word were you using?

George Bekey: Well, this was an artificial quadruped and so I don't know. I don't remember whether we used the word robot. I'm not sure, to be honest with you. But I remember that also somewhere, it may have been in the 1970s or '80s when I would talk to people from DARPA, and I used the word robots, I remember these people telling me, if you use that word in a proposal we can guarantee you will not be funded because that's considered a bad word at DARPA because so much money has been wasted on robots and they don't work. But then they came back with a vengeance, so I've seen some of these trends in society as well. Anyway, that machine was very interesting. It really did walk very nicely. It didn't have any ankles, it had a large horizontal bar to provide lateral stability, but it had hip and knee joints, and so it was able to pace and walk and trot and so on.

Q: And what kind of control system did it use?

George Bekey: It was a digital control system designed largely by Bob McGee. Let me borrow the book for just a second. Well there were some ideas there which appeared in later things that I worked on. So I always felt that an animal or a human does not control every miniscule element of the motion of their limbs. Right? I don't solve differential equations of motion in my legs when I'm walking. So there's a combination of learning and autonomy that occurs in the way in which we do this and so we adjust the nervous system in the process of learning from childhood. By learning you don't have to solve the inverse kinematics of motion for every step that you take, because that would require matrix inversion and things of that kind which you certainly don't do in our heads. So those principles appeared here and we called it, at the time, <audio skips> autonomy, so that each limb was as autonomous as possible on its own and that principle showed up in other things we did later.

Q: Like what?

George Bekey: I guess I shouldn't have said that, and I should've known you would ask me how it showed up later. It also showed up when we began to work on hands, because you see the hand was meant to be completely autonomous. It was triggered by a single contact, and then it would autonomously close. So it certainly showed up there.

Q: You think there's some relation to the subsumption architecture approach that Rodney Brooks developed later?

George Bekey: Oh yes.

Q: Similar concepts.

George Bekey: Well certainly similar. Rod and I are friends and I like him a lot and I respect his work enormously. In fact, the first 6-legged robot we built in the lab we called Rodney. When I told him that he said, “Thanks a lot.” <laughs>

Q: So were there any other robot-like machines that you built before you called it robotics?

George Bekey: Frankly, I don't remember, but I don't think so because after this, as I told you, I went into other things. I was trying to do visual signal processing, and hybrid computing, and one thing and another. So I don't think – I don't remember, but I don't think so. I think that basically the idea of these kinds of autonomous machines sort of disappeared from my current things and then reappeared when we formally started the robotics program in the 1980s.

Q: Do you think you would have maintained your interest in analog computation if you'd had the kind of high performance digital computation we have now?

George Bekey: It's – I'm not sure. Oh by the way, the young man that I worked with who came with an interest in robotics was Barry Soroka, S-O-R-O-K-A. So Barry worked with me for three years. And, in spite of my best efforts, I could never get him to write a paper, even when I outlined it and wrote the introduction for him. He just didn't have the discipline to write. And USC is a publish or perish school. So after three years Barry left and went to Cal State University – Cal State Polytechnic University in Pomona, where he became chairman of computer science. Very bright guy and wonderful sense of humor, and a great breadth of interest in art and so on. He and the woman who worked in the dean's office jointly composed an opera at USC where all the characters were faculty members. <laughs>

Q: So what were the first robot helicopters?

George Bekey: Well there was a competition for robot helicopters at Georgia Tech. And so I entered our lab into the competition even though we had never done it before. But I had two outstanding Ph.D. students, Andy Fagg and Tony Lewis, both of whom were very imaginative. And we, basically, turned them loose on the project. So this competition had – I've forgotten. Let me guess, maybe 15 entries that arrived with various flying vehicles. And the goal was for the vehicle to fly from a starting position into an enclosure area, pick up something, and then bring it back. The first year of the competition, which – let me guess, must have been in the mid 80s, but I don't remember exactly. None of the vehicles actually left the ground. They all crashed, or disintegrated, or fell apart in some way. So, actually, the winner was declared to be the vehicle which fell in the direction of the target. <laughs> By the second year, they were beginning to fly. And they were unusual creatures. There were vehicles with four propellers, and so on. And so our helicopter actually did quite well. And, though I think it may have been Tony Lewis who came up with a formula for calculating how much it would cost to repair it after every crash. And the formula was it would cost a hundred dollars times the number of feet above the ground at which it failed. So if it failed ten feet above the ground, that'd mean it would cost a thousand dollars to fix it, you see. And as a result of that we flew them very low until the 1990s where we began to do really serious high altitude flying. And it's really Gaurav who got much of that work done.

Q: So who are some of your other students and what kind of work have they gone on to do?

George Bekey: Well I've had – I graduated thirty-eight Ph.D.s in my forty years at USC, so almost one a year. And so, of course, the first ones were not connected with robotics. But after some time in the 1980s, they were all in robotics. And so what can I tell you? So let me begin with a few – the one's that I can remember, immediately. We've mentioned Tony Lewis, whom you know, who is still in the field and doing very well. Huan Liu is now at Arizona State University in the computer science department. And he worked on grasping, and models of grasping, and so on. He's completely left that area. He now does information retrieval from social networks, so completely different story. He's completely changed fields. Let's see who else? Andrew Fagg is at a university in the south – no east. And he has, the last time I heard – I haven't heard from him at least five years, but he was building a humanoid robot. And so he's still in the field. Who else worked in robotics, specifically? Yeah, I mentioned Fred Hadaegh earlier who does this group flying – synchronized group flying of satellites. He didn't work in robotics at all in his Ph.D. program. He was working on methods of doing system identification, which is one of my interests for twenty or thirty years. That is given input and output measurements of a system; can you build a mathematical model of how those are connected? And you can see that this grew out of my work with human operators, see? So I was interested in connecting the sensory input with the manual control output. And some of those projects were very successful. And others, which I still thought were a great idea, failed fairly miserably.

So I'll give you one example. I proposed a project to JPL, which was funded, where I said people who have – paraplegics who can't move their legs, some of them actually have, in principle, the possibility of moving with canes, or with walkers, or the equivalent. But they won't walk with canes because they're afraid of falling. And that's because they don't have the afferent signals from the nervous system that would give them the indication they were starting to fall. So I said why don't we do this? Why don't we install accelerometers on their belt that would provide an indication of falling, either forward-backwards, or laterally, or create a vector to show you that you're falling at 45 degrees, or whatever's happening? Okay? And then use that information: let's say that you're falling to the right, and use the information to tickle you on the left hand side. So now that gives you the indication what you should do is to push on your canes, or whatever, to straighten up the body in that direction. So I still thought that was one of the better ideas I had. But what I didn't figure with was – by the way, it worked very well, but for a short time. Why? Because the human skin habituates. And the electrical signals that we used for tickling, they didn't feel them after a while. So you had to raise the power. And then eventually we got the point it was burning the skin. You see? So you can't go that high. So this – you can see how that would happen, right? So, anyway, so that's why that never became a Ph.D. thesis.

Now let's see who else did work in robotics, specifically? Danilo Bassi who is currently in the United States at Valparaiso University in Pennsylvania, I think. He was <break in audio>

George Bekey: Back to Chile after getting his degree, and stayed there for many years. So he worked on control of manipulators using genetic algorithms and other related mathematical methods. So he returned to Chile and then became interested in using robots in mining. There are a number of copper mines in Chile. And so he got interested in this. And then he tried to form – for a long time was working on forming a consortium of American and Chilean companies to do mining robotics. And he formed a mining consortium, and so on. He was never able to get it quite off the ground. And now he's trying very hard to get an immigration visa so he can come to the United States permanently. He's here on some kind of a temporary visa. I just wrote a letter for him. So he really moved – so he really was in robotics in the beginning, but what he did was in something quite different after that. We never did anything on mining. I'd have to pick up a list of my students, which I can certainly do.

Q: We can just go on for now.

George Bekey: Yeah, let's just go on. But, as I say, there are many of them.

Q: Who are some of the people that you've collaborated with over the years, other institutions or at USC?

George Bekey: Well, Michael Arbib. Michael and I had several joint grants from the National Science Foundation. And so we worked on those things together. Who else did I –? I collaborated with Bob McGhee, the man who I mentioned to you was involved in the construction of the original horse. Bob left from USC and went to Ohio State University, where he built a humongous four-legged walking machine that was originally designed to carry soldiers in Malaysia, or someplace. It was never successful for that purpose, but it was a remarkable machine. And from there, when he retired from Ohio State, he went to the Navy Post-Graduate School, from which he's now retired also. And there he was working on robot fish. So he's a man who was in robotics from the very beginning and pretty much stayed with it from the time of the 1960s.

Q: What was his name again?

George Bekey: McGhee, M-C-G-H-E-E. Now let's see who – with whom –?

Q: Is he still in Monterey?

George Bekey: He still lives in Monterey. And he'll be at the talk on Friday. So you'll have a chance to meet him. Yeah, right. You should look him up on Google. And I think you'll find that he's a very interesting guy. He's pretty much dropped all professional work when he retired from there, concentrating on his grandchildren, I think. So, but that was – that's now been probably four years, five years. And I believe about a year, year and half ago, his wife died. And that confirmed his sort of leaving aside- Though I've been told that one of his students, who is a faculty member of the Navy Post-Graduate School, now does some technical collaboration with him. So he may have returned a little bit. Sometimes, we as robotics, it gets in our blood, and we can't quite let it go. And it sort of comes back. Where were we, I'm sorry? You asked me something else.

Q: Collaborators.

George Bekey: Oh, collaborative, okay. So, Bob and I had some joint grants with – I think with the Army research office, or AFOSR. I don't remember at this point. My last major contracts, which were DARPA contracts, Maja and Gaurav were co-PIs. I was a PI and they were assistant, or co-PIs. And then, actually, when I – a year or so after Maja came, I turned it over to her because I was too busy. I was working in the dean's office. I was an associate dean and she is too, except that she's super-human and can do several things at once, which I can't do. Okay, now let's see. Who were other collaborators? I never formally collaborated with Rod Brooks. I wrote some joint papers with people like – see I think Arthur Sanderson at RPI. Do you know him? Okay, so Art Sanderson was a – actually he was president of the IEEE Robotics and Automation Society before I was in the, maybe, mid 1990s. And he's built some very interesting machines at RPI. The latest one, which he did jointly with the Navy in some context, is a fairly large ocean going vehicle, which is completely covered with solar cells on its horizontal surface. And so what it does, it charges up all its batteries and then dives. And then behaves like a submarine until it needs to be charged again, and then it comes back up and charges up. So that's a very interesting robot vehicle, very interesting. Well I'm sure I'll think of other collaborators before the time goes too far.

Q: Can you talk a little bit about the Society of Robotics and your involvement with it?

George Bekey: Sure. So in – we're talking fifty years, right? So we're talking about the 1960s. And so at that time, one of the leaders of the – well there were several people who were among the original leadership of the society, George Saridis was one of them. He was actually probably considered the founder, and he was the first president, I believe, of the Society. I'm not sure about that, but I think so. George Saridis eventually moved back to Greece, where he came from. And I believe he died about five years ago, seven years ago, something like that. But George was a very imaginative and hard working guy. He and I collaborated in the organization and running of a couple conferences. One of them was the International Federation for Automatic Control

Conference on System Identification. And so the proceedings of that are available, edited by George Saridis and George Bekey, or the other way around. I've forgotten which. But that's what we did. So I knew George fairly well.

The other people who were involved in the original society, one of them was Antal Bejczy who was probably, historically, the most interesting roboticist at JPL. He's now retired, but still lives in Pasadena. B-E-J-C-Z-Y. And he goes by Tony, though his real name is A-N-T-A-L. But so Tony Bejczy was a pioneer in space robotics. And so he was involved in the construction of some of the first manipulators that were used in space and prototypes of the big space arms. The ones on the shuttle now are built in Canada, but there were a number of prototypes built at JPL. He was also, I believe, the inventor of providing rate feedback for manipulators. The point here is, for anyone who's worked in control theory, you realize that if you don't give – the advantage of being able to read the velocity when something is moving, is that you can get some – a measure of anticipation. See, let's say for example I'm aiming from here to here. And if I want to use position control, when I shut it off, the system has inertia. It'll overshoot. If I measure the velocity, then I can use a combination of position and velocity and have it reach, precisely, the target. So I believe he was the first person to use that in robot arms. And that's one of the strong features of DaVinci surgical robots. They use rate feedback, which I think makes them significantly more stable that it would be if used only position control. So Tony was one of the other early people. There were two or three others and, I believe, at least one or two of them has since passed on. And I don't – I've not been in any contact with them. Larry Ho from Harvard was an early participant, but his field was not robots in the way in which I knew it. It was more – well, I don't remember what he did, but it wasn't exactly robots.

Q: And were there other robotics societies? Or was that the first?

George Bekey: At the time when we started this one, I believe the Robotics Society of Japan was already in existence. And so we really became the second society. And then somewhere, about the same time, or perhaps a little later I don't remember, the ASME, the American Society of Mechanical Engineers, began to do work in robotics primarily through one of their sections that dealt with control and structures and so on. But I think that this was really the original society. And as the IEEE does – you know when your form a new society, they usually don't give the society name right away. That's reserved for people after some level of maturity, apparently. So it's called a group or something like that, and it's – so it was jointly sponsored by two or three other societies initially. And so we were not permitted to call our journal the Transactions at that time. Again, it's another IEEE formula. I think it was called – it was called what? Maybe – well, the society was always called Robotics and Automation. It always had the automation component in it as well as straight robotics. But the word transactions only came when we formally called it a society, and that took about five years. I was president from 1996 to '98. I'm pretty sure that that's right. But I had been active from the beginning because I had started the journal. Oh, it was called the IEEE Journal of Robotics and Automation, that was the word. And we were not permitted to call it Transactions until the society was formalized.

Q: But you started the journal at the same time as–?

George Bekey: Yes, the – it took about a year longer because we formed the society, and then I spent about a year fighting with the IEEE bureaucracy to get this thing started.

Q: So what year was that, then? Do you remember?

George Bekey: I don't. We could probably take the current Transactions and look at the volume number and work back. Should we do that? It'd be interesting. I don't remember. I mean, obviously, I could look back at my various CVs. Okay this is volume 26 dated 2010. So that would make it 1984, right?

Q: '84, yeah. So that would have been as Transactions.

George Bekey: I think they kept the volume numbers continuous. In other words, journal volume – let's say that there was journal volume 5, then when it became Transactions, it became volume 6. They didn't start all over again.

Q: But it was a volume every 2 years, or –?

George Bekey: No, no the volume was for the whole year. So there were, I think initially we had, maybe, four issues a year, quarterly.

Q: And then the – you were also involved with the Autonomous Robots journal?

George Bekey: Yes, well that started significantly later. And I was at one of the IEEE robotics conferences, and I was chatting with the editor of Kluwer publishers. Kluwer no longer exists. They were taken over by Springer. Okay? But we were chatting and he said, "You know, we should really do something in robotics. So would you be interested?" I said, "Sure, let's start it." I mean that's how it happened. And so then Kluwer sent out questionnaires to every member of the society and some other people to try to get feedback about whether there was really a need or an interest in another journal. And so that's what happened. So we got it. Now, the year I can tell you very easily because that hasn't changed. So that's still in the continuous numbering, and I think it was roughly twenty years ago. Volume 29. Now that's interesting because that means that I may be wrong, that the journal volumes terminated and Transactions volumes began.

Q: Yeah, that could be.

George Bekey: Because this was definitely later. Oh, but in – but I believe Autonomous Robots, for a long time, numbered their volumes twice a year. And so, I am no longer sure when this thing started. I can't be sure. You can find out, that's right. So that's the story with Autonomous Robots. I also – I have in my – in the bedroom closet because there wasn't enough room in here – in my office. But I have volume number one. So if you're really interested in this I can pull it up and look at it.

Q: Oh wow, yeah, actually.

George Bekey: Rodney Brooks was one of the authors involved in volume one number one.

Q: So what do you consider your most successful, or your proudest robotic accomplishment?

George Bekey: Well I think that even though it was never a commercial success, I thought the work on robot hands was one of the things that I always was most pleased with. And there my collaborator was Professor Tomovich from Yugoslavia, you see? So that was a very clear collaboration. And he would travel to the states once a year. And I went to Belgrade about once a year. So that was a very interesting and very fruitful collaboration. And I still have contacts with one of the people from Yugoslavia who worked on the original project who is still there. So that was one. And then the second thing was the project that Tony worked on, which I always thought was one of the major accomplishments of our lab, which is the project on using genetic algorithms to enable a robot to learn how to walk. And I think that was actually probably one of the more successful things in the – and I can't – Andy Frank who built that four-legged robot in the 1960s was formally my student, that is I was his major professor. But he was guided much more by Bob McGhee than by me because I didn't understand the digital technology very well having just grown out of the analog side. And I was moving into the digital, whereas Bob stared on the digital side. And he had some analog background, as well.

Q: What kind of computers were you using at that point?

George Bekey: Well when I came to USC we had – the only digital computers we had – that the university had were some ancient Honeywell computers. Honeywell no longer makes general-purpose digital computers. And so – and it was – as I recall, it was difficult to keep them running. But they were the only machines around. And then in a year or so after I came, I wrote a proposal to NSF to get a digital computer that we could use as part of the hybrid system. Beckman Instruments, where I had worked, gave us an analog. And then NSF gave us enough money to – well we had enough money to buy maybe half of an IBM 1620. The 1620 was a process control computer. It was originally was a serial digital computer, which meant that each word processes each bit serially one at a time, rather than going in parallel. This was early technology – [recording ends abruptly]

Q: So you were getting an IBM –?

George Bekey: IBM 1620 and then we formed, we created this hybrid system by connecting those things together. The Beckman analog computer was very large. It was a vacuum tube computer and –

Q: What was it? What was it designed for?

George Bekey: It was designed to be a general purpose computer.

Q: General purpose analog.

George Bekey: Only general purpose analog computer and the – don't forget that the early digital computers, the earliest ones actually had patch boards also and you had to do a certain amount of programming by moving cords around and then the stored programs came later on digital computers. So and they were very slow. So the idea of a joint, of a combined analog/digital system was really a very interesting thing at that time and you know we learned a lot from doing it. I was at TRW before coming to USC. I'd actually been there full time and then I went on part time and went back to campus to write my thesis, but I did almost all my coursework while I was working at TRW and there we built a sizeable hybrid computer and I've forgotten what the digital component was, but the idea there was to try to use the hybrid computer to simulate the flight of intercontinental missiles because we had been using analog computers to study the high speed dynamics, high frequency dynamics of rockets because these early rockets, like the Atlas for example, are very flexible. They had to be because the skin was made as light as possible so that they would carry as much of a payload for these long distances. So they were full of liquid fuels and they were very flexible.

So there were two phenomena that occurred. One was bending. So these things bent and not only this way, which is in the first bending mode, but also this way and even this way. They were to the point where there were three frequencies where we had to look at because there was significant bending in the first, second, and third bending modes and then the fuel, as a result of this bending, the fuel began to slosh. This was liquid fuel and if you've ever sat on an airplane and have coffee sloshing in your cup, you realize that if you excite it improperly, it'll slosh right out of the cup, right? And that's why airplane cups often have a lip so as to prevent the coffee from or whatever liquid you have from sloshing out. So those things happened at such high frequencies it was impossible to do on a digital computer. They were too slow. So what we thought was let's do all the high frequency dynamics, control system sloshing, bending on the analog and use the digital computer to integrate the equations of motion so we can maintain the accuracy that's needed to hit within a few feet of a 5,000-mile trajectory. Okay? Because the analog computer drifts. It's not able to maintain precision for that long a period of time. So it was – I still think it was a hell of a good idea and so you know my name is associated with some of those early experiments.

We succeeded in building it, but it took us a year longer to get it fully debugged and the reason was that while we had taken into account the possible advantages of the analog on the digital side, we didn't take into account the disadvantages and the disadvantages were that the digital computer accumulated round-off errors and the analog computer drifted anyway, so we still had problems with it and so it took us a year longer and the Air Force just didn't want to wait any longer. I mean after we had promised them we would have simulations that they could use for guiding their missiles, they had a schedule to meet and they couldn't wait any longer, so they flew the first missiles toward some island in the Pacific and what they discovered was that the – and experimentally from seeing it is that the high speed oscillations had a negligible effect on the trajectory. So therefore you could solve them separately and it didn't matter how long it took on the digital computer to do the other equations because it was not relevant, you see. You could do them separately. So that's what happened and so this was not robotics, but it was certainly part of my own background and had to do with learning computer technology from both sides.

Q: Yeah and at that time analog and digital computation were sort of comparable in their –

George Bekey: Yes, in the late '50s and early '60s there was a great deal of competition in fact and at the Western Joint Computer Conferences there were always panels that had to do with analog versus digital and that kind of thing. In fact I'll even tell you about a poem. The worst of computing perversion is analog to digital conversion.

Q: So why do you think digital was so successful in the end?

George Bekey: Well, I mean increasing speed. I mean we're still – this is the benefit of the early days of Moore's Law. They began to move away from vacuum tubes and move to a solid state switching and faster and faster speeds. The analog simply couldn't keep up. On the other hand, there's been a rebirth of analog computing at the chip level. So there are clearly advantages to being able to do some things and without having to convert things into digital form, process on the digital and then reconvert back, you see.

Q: The analog VLSI.

George Bekey: Right, absolutely. Analog VLSI is exactly it. Okay, and now let me think back. Would you like me to look up the names of former students and talk about them for a little while?

Q: Sure.

George Bekey: Was at Rockwell. Okay, so on the robotics side Huan Liu who I mentioned to you is now at Arizona State. He did grasping, knowledge based planning for grasping with robot hands. Dit-Yan Yeung who was in Hong Kong worked on non-linearities in connectionist or genetic algorithm kind of learning, but he's completely dropped all that sort of interest. He does other things now, so he has nothing to do with it at all. Patti Koenig, with whom I've almost no contact anymore, she was at JPL for many years and I don't know where she is now. So she came to me saying, "I'd like to do a BHD thesis, but I really would like to do something with horses because I'm a horse woman and I like horses and particularly I like horses that do dressage and other unusual movements of one kind or another." So we came up with the following kind of peculiar project.

So the idea was – so I went out and bought a plastic horse, full-size plastic horse, and we instrumented the horse in such a way that if you, you could pick up signals from pulling on the reins because we put string gages on the two sides of the mouth of this horse and then we put pressure sensors on the flanks so that if you kick it, you could pick up that signal. Okay, so then those were used as inputs to a simulated horse on the computer screen so that you could now see a person would be sitting as a rider on the horse and they would command it and the simulated horse would move accordingly and so the idea was that you could train people by this combination of actually sitting on a saddle on a full-size horse, but doing the control on the computer and people who came to use it who were experienced riders said that it was spooky how realistic it was and they would begin to forget that they were sitting on a mechanical horse and visualized themselves on the simulated horse on a big screen. So was that robotics? Well, in a way.

Q: <inaudible>

George Bekey: That's right and when she published – oh by the way, the simulator horse had unusual colors. So she published some of this stuff about a green horse and so that was Patti.

Then Arvin Agah who is now a professor at the University of Kansas did his work on coordination in robot colonies and so he initially did a simulation in which he had a hundred simulated robots on the screen and the idea was that these robots would be tasked with picking up objects of one kind or another. Some of the objects were smaller, some were larger. The robots were able to call for help if they found an object that was too big for themselves to carry and so a second one would come to help. There was a lot of interesting sociological experiments in that particular study. There was a – we discovered that depending on how wide you made the communication radius, that is how far each robot's signal would carry out to the rest of the colony, what you could do is you could make the robots move in clusters rather than individually, but if you made the radius either too large or too small, I can't remember, then they would begin to move as individuals. So there were many interesting things in this and he actually built some small physical robots that were used to pick up a piece of pipe and carry it. It was still two robots cooperating. Maja was the original developer of the multi-robot thing at MIT when she was doing her thesis. She was able to get something like twenty of these small robots operating and she called it a nerd herd. You probably have heard this before. She was very good at that.

Okay, so that's – Tony Lewis worked on locomotion controllers in robots and animals and so he was very interested in models of the spinal cord and the spinal reflexes and how they could be imitated in robots. He's always had an interest in the biology, particularly the nervous system as well as and locomotion as well as building robots. John Kim is a very interesting person. I was consulting at the time at a chronic rehabilitation hospital in Downey, California called the Rancho Los Amigos Medical Center and I was really interested in sort of how you use knowledge based methods to try to understand what's going on. I didn't really want to build "expert systems" in artificial intelligence, but I usually refer to them as knowledge based systems to see how you could use accumulated knowledge to make decisions. So the lab where I was consulting was concerned primarily with issues of human walking, both normal walking and pathological walking like with people with cerebral palsy and so on or people who had had spinal cord injuries and that kind of event. So and the physician in charge kept saying, "You know we really don't know when we see a particular pathology which muscles are responsible and we might be able to do corrective surgery if we knew, but the trouble is there are 20-some muscles in the lower leg and you know in the legs and so therefore we have to identify which ones they are." So what I did is the same thing we would normally do and try to build this kind of a system in AI.

What we did is we hung like butcher paper around a whole gigantic conference room and then I began to interview the various doctors about what the conditions are that they saw and what things could happen if a particular muscle was defective or inactive and so on and so out of this, this fellow John Kim developed a diagnostic knowledge base to make predictions about which muscles are responsible for particular gait pathologies and it was very successful. This worked very well. I'm not sure how well it was used, but it certainly did work. So he had a Ph.D. in computer science and then he worked in AI and then he graduated and decided that this was really not for him and he got a job as an intern in a law firm which had dealt primarily in patents and patent law and as you know patent attorneys usually employ engineers and computer scientists because they need the background. So they sent him to law school and he spent almost three years going to law school while working part time at the law firm and then he decided that law was not for him. So this was career change number two. He currently is – he went to school again and he's now the minister of a Korean church in one of the suburbs of Los Angeles and he's happy as a, whatever you want to say, a clam, whatever, but he's very happy. So I don't know whether that's relevant or a story that you personally would find interesting.

Q: Yeah, yeah.

George Bekey: Gaurav Sukhatme worked on ways of evaluating autonomous mobile robots and he's the one who compared the legged and wheeled robots on the surface of Mars. Alberto Behar worked on intelligent telerobots, smaller robots that could be sent to a space – sent by space vehicle either to a planet or a comet or some other vehicle to do exploration and some of the stuff was done in hardware and some was done in simulation. Ayanna Howard, who is now a professor at Georgia Tech in electrical engineering, did her dissertation on grasping, but it was grasping of deformable objects, which nobody had done before. Everybody grasped rigid objects, but now if you grasp something rubbery that squishes, the dynamics become completely different and her work was beautiful and she's still in robotics. She now – so she teaches in electrical engineering and but I don't know exactly what she does, but she's definitely still in the field. Jim Montgomery did his thesis on robot helicopter flying and still does that kind of work at JPL. He still flies robot helicopters or simulated helicopters to be used for planetary exploration and things of that kind. And my last student is Stergios Roumeliotis who is now an associate professor of computer science at the University of Minnesota and he did his work on using Kalman filters and other statistical methods to help localize robots to determine where they are from some surrounding measurements. This is the usual question, which is sometimes referred to as the kidnapped robot problem. What information does a robot have to have if you kidnap it and put it down somewhere to determine where it is.

Q: So what do you see as the biggest challenges and problems facing robotics into the future?

George Bekey: Well, so I think among the current problems of greatest interest in robotics, one of them is certainly human-robot interaction, the ways in which humans and robots can not only interact, but collaborate, work together, and a lot of this is related to the increasing capability of humanoid robots so that we mentioned sensing before, but clearly humanoids do a lot more than sensing. They not only move, they not only sense, but they process information in increasingly humanlike ways and my feeling is that it's not necessary to build identical models of the human brain. What we want to do is to try to build into robots the functionality in some sense of aspects of the brain. So I think the greatest challenges, I believe, will come in two or three different ways. So one way is to try to continue to improve the capability of humanoids so they can interact with human beings in a more and more significant way so that they can receive commands by voice; they can interpret our gestures; they can display emotions. A very important research area, robot emotions, at the present time. And that means that a robot then could be a genuine household helper. It wouldn't be Rosie from the cartoons, but it certainly could be a genuine household helper. So and not simply a unifunctional device like a Roomba vacuum cleaner, you see. I mean we're talking about something that has a great variety of capabilities and these things are not easy.

I mean my friend, Rudiger Dillmann in Germany has been working for the last five or six years at building a kitchen helper robot that's supposed to clear the table, pick up all the dishes, put them in the dishwasher and so on and it's not an easy problem. I mean it displays all the difficulties of coordination, sensing, activation and so on. He's now able to – the robot now stacks dishes in the dishwasher reasonably well, but they use plastic dishes to make sure that they don't break. So it's – these are not easy things. So that's one of the areas that I think. And the second area that grows directly out of that is that I think society is going to have to pay attention to the way in which robots relate to people and what functions they perform in society. As you know, Kurzweil talks about sometime in 2020 or so that robots will demand to be treated before the law as if they were humans and they will succeed, he says. Okay, I don't know about that, but I do believe that we have no basis in our legal system currently for how to deal with quasi-human beings, with – we have no way of handling issues of responsibility and ethics and so on. So these are – that's one reason why I'm so interested in now in this whole area of robot ethics. So I think that those issues and that includes, by the way, the use of robots in the military and robots in war – as I'm sure you know there are now more than 40 countries that have military robotics programs. We've had a monopoly on the use of robots in the field, but we no longer have a monopoly on guns. Every country has guns, you see, so I don't think we'll have a monopoly on robots either and that means that there will have to be some pretty dramatic –

Q: Okay.

George Bekey: I think autonomous vehicles will be one of the major challenges in robotics from the time that Sebastian Thrun won the DARPA Challenge as you know, the idea of using robot vehicles has become much more prevalent and there are programs in Europe as you know as well as in the United States and other places that could create these vehicles, but again I think we need to find ways in which we can adapt to such vehicles in terms of our legal system. We don't have the appropriate rules of the road. We don't have the appropriate vehicle codes and we don't have the right questions of risk and responsibility. The third area that intrigues me a great deal is robots in healthcare in a variety of ways. We know that we have robot surgery devices like the DaVinci system, but it's really a teleoperated robot and I think that the time will come here as well as in the military that these robots will have increasing degrees of autonomy and will be able to perform surgery on their own just like I believe the robots in a decade or so in some unknown conflict would be able to find their own targets and release their own missiles without human immediate consent. So but in healthcare, this of course raises a whole series of new ethical questions as well and if I wake up from a surgery and it was done by a robot and I thought it was going to be done by a physician, by a human physician, and it didn't go well, then whom do I sue? You see and to what extent will hospital administrators begin to rely on robots to perform surgeries if it's less expensive both for the hospital and for the patient?

So these are things again that we don't know how to do. We don't know how to deal with the – we don't have the social and I would say emotional machinery for integrating robots into society in any kind of a proper way. So we need legal and social frameworks which we kind of don't have and I think that's going to be one of our biggest problems. A second area in healthcare is the prosthetics and where I think robots are already playing an important role, the Otto Bock computer-controlled knee, which is fitted to nearly all the amputees coming from Iraq or Afghanistan, is a wonderful device, but it's only the first one of what I think will be many more. There's a large DARPA program to create artificial arms with the full functionality of a human arm. So those are robot arms. They're clearly autonomous devices with a lot of sensors and the ability to actuate, but there are lots of other things going on. You see there are programs for replacement of portions of the central nervous system including portions of the brain by chips, which will be able to pick up information from the outside world that would normally be sensed and sent to them by the eyes or you know and so on or by stretch receptors in muscles and then this chip will process the information in a way in which say a diseased section of the brain would have processed them and then provide output signals to the world.

So I think that there is an almost unlimited horizon in what can be done in creating new bionic people and many of these replacements will be from my point of view robots and you see so that puts the whole thing into a larger context in which we really begin to ask ourselves the question of what it really means to be human and to what extent do robots and humans share concerns and to what extent are they completely different. You know I told you that I had spent some time in school of religion and even now in the years when I don't teach robotics, I teach a class of world religions here at the California Polytechnic University at Cal Poly where I don't do comparative religions in the usual sense, but I do talk about Hinduism and Zoroastrianism and Buddhism and so on and I try to look for the ways in which people in those traditions look at the meaning of life and their relationship to the universe. Now how can you, in any one of these philosophical traditions, let me call them philosophies rather than religions? How can you not relate to something which is quasi-human? I don't know if you've seen the movie "Bicentennial Man"? Okay. Well now that raises the kind of questions that I'm raising here, you see.

Here was a robot with the greatest desire to be human even though it meant becoming mortal and it clearly makes wonderful theater, but I think it also raises the kind of question that I was asking from the very beginning. To what extent does working on robots teach us something about ourselves and what it is that makes us unique and special? It's clearly not the things that we used to say. I mean there was a time when – I mean I remember when I was in college there was a book called "Giant Brains" and the reason it was called that is because it referred to the first machines which were able to compute astronomical tables by doing huge numbers of additions and multiplications and divisions and print them out and we thought that was the activity of the brain. You see I mean now it's considered so trivial that we don't look at it at all. So I don't know if that helps, but I think in terms of the future, I really think that as robots become more capable and more able to interact with humans and on many levels that I think we'll begin to ask ourselves more and more of these kinds of questions and who knows what the future holds, but it certainly won't be boring, I can tell you that.

Q: In terms of technical challenges, what do you see as the big problems facing robotics?

George Bekey: In the design of humanoid robots, for example, I think that there are still issues involving actuation. Sensing we've done very well. Sensors have become small and have enormous capabilities, but our actuators are still too heavy and too big and so I think we still need to find better ways of imitating biology in the design of arms and legs and tentacles or whatever we might use, which are lighter and more flexible and so on. So I think that's still a major area of concern and then obviously the question of how do we model the activities of the brain and I don't need to tell you there are many projects in this area going on around the world. People are doing one thing or another with respect to the brain and eventually some of these efforts will become integrated. Increasingly we're beginning to talk about having a direct connection with the brain even by implants, by implanting electrodes directly into the central nervous system. So from those we should be able to derive the kind of information that might be useful in designing brains for robots. But I think that's a – that should keep us and our children busy for a while.

Q: And over the course of your career, what do you see as having been the biggest breakthroughs or innovations in robotics?

George Bekey: So I think that what has helped robots the most is Moore's Law; the fact that we can do so much computing so fast in such small packages that use so little power and cost so little. I mean that's the most interesting thing to me, you see. You talk to people now who do computer design and they basically tell you that the hardware is for free. The cost is in the software and that was inconceivable when I was in college, where the hardware was all the cost. We didn't have enough software to know how to price it, but hardware was extremely expensive. One of the first computers at UCLA when I was a student was called the SWAC, Western Automatic something or other computer and it used cathode ray tubes for memory, huge banks of cathode ray tubes and you can imagine now the cost of that kind of memory. See it just was completely different from where we are now. So I think in terms of what's improved in robotics, it's happened on many fronts, but I think that Moore's Law has been one of the major sources of improvement because we can now build robots with a lot of intelligence and for very little money, using very little power.

So I think that's been one of the major changes and I think in the last decade or so social acceptance of robots in the United States has improved dramatically. I think part of it is due to Rod Brooks and the Roomba, of which as you know something like four million have been sold, so now it becomes a commodity rather than some kind of an unusual specialty item and whereas in Japan robots have been a much more accepted part of the culture for many, many years, in the United States they were not. There was always this question about how soon will they take over and so but I think that that's one of the changes that I've seen so that now it's expected that robots will be doing many things that are not now possible for them and that it's becoming much more accepted in society. For the United States that's been a relatively recent development. Not for Japan, but certainly for the United States.

I'm concerned about – oh, one of the things that we desperately need, to come back to your earlier question, we need robots to act as live-in assistants for the elderly because with the aging population that we have, we simply cannot afford as a society to put everyone into old folks' homes. It just costs too much. We just don't have the resources to do it as a country when as you know the usual age pyramid is now inverted so that the number of people over 80 is becoming significant. So the answer is to let people stay in their homes, but provide them with one or more robots to assist them and we're doing very little in that area in the United States. I led a team supported by NSF to study the status of robotics in Asia and Europe five years ago in 2006, four years ago, and every lab we visited in Japan and South Korea and most of the labs in Europe were working on eldercare robots and so I think unless things change in terms of finding ways of supporting such developments with venture capital or elsewhere in this country, I think another 20 years we'll be importing all those robots from Europe or Japan if we have the money, and we may not. But that's another story.

Q: Anything else you'd like to add?

George Bekey: Well I'd like just to say what I said earlier. I really think that robotics is an incredibly fascinating field of study because it enables you to combine interests in psychology and sociology and philosophy and engineering and computer science and I don't know of any other area of study which provides that kind of breadth and the possibility of integrating all these areas. So that's my feeling. I'd like to say to young people if you're looking for a challenging field, go into robotics.