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# Ken Waldron

An interview conducted by
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with
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**Q:** So if we could start by having you say your name and where you were born.

**Ken Waldron:** My name is Ken Waldron. I was born in Sydney, Australia and most of my education was at the University of Sydney. I have a Bachelor of Engineering degree and a Master of Engineering Science from there. And I got my PhD here at Stanford with Bernie Roth. And I subsequently did receive a Doctor of Engineering degree from the University of Sydney in 1999.

**Q:** And so how did you get interested in engineering to begin with?

**Ken Waldron:** I've often wondered about that <laughs>. Seemed like a good idea at the time I guess. I had a grandfather who worked as a draftsman at the water board in Sydney and he kind of fed me stuff when I was a teenager, which I guess got me interested. And then I got a traineeship from the Australian Steel Industry which meant that I went to work for them in vacations and I got some salary and stuff like that so that seemed like a very good idea at the time.

**Q:** And what made you decide to come to the States to continue your education?

**Ken Waldron:** Well when I came to consider doing a doctoral degree most advanced students in Australia at the time went to England. I was interested in things that people here in the States were better at than anybody in England and I didn't want to do what everybody else did anyone so I wound up coming here.

**Q:** What were some of the things that the U.S. was better at?

**Ken Waldron:** Well at the time it was mechanism and machine theory, kinematics and dynamics of mechanisms. It wasn't – well there was hardly anybody in England working in that area at the time. So it was much easier to find people here or in Germany or someplace like that.

**Q:** And when did you first meet Bernie Roth?

**Ken Waldron:** When I came here as a graduate student in 1965, June 1965.

**Q:** How did you meet him?

**Ken Waldron:** How did I meet him? I think I'd just arrived and I'd climbed up a big flight of stairs in Engineering Corner to his office on the top floor, walked in and said "Here I am." <laughs>

**Q:** Did you know him before you came here?

**Ken Waldron:** We'd corresponded in our research assistantships so he knew I was coming.

**Q:** So you came to be his student?

**Ken Waldron:** Yes.

**Q:** And what were some of the projects that you worked on with Bernie in those early years?

**Ken Waldron:** Oh, well my doctoral thesis was actually a topic I'd brought with me, that I'd been tinkering around with in Australia, which was in the area of mobility of linkages. Just counting links and identifying how many degrees of freedom the whole assemblage would have based on its geometry. But at the time the really early work in robotics was going on too so I sort of got involved in that by osmosis.

**Q:** So what kind of work in robotics did you see or get involved in?

**Ken Waldron:** Well the last year I was here, Bernie went on sabbatical and I was put on as an acting assistant professor to teach his courses. And at the time, Vic Scheinman was designing the Stanford Arm and so I wound up being his advisor of record. So I was involved in that project. Also, I was sharing an office with Don Piper and Mike Kahn at that time when Don was doing one of the first versions of inverse rate kinematics. And I happened to know a good deal about the algebraic geometry involved so we talked about that quite a bit. So it wasn't my work but I got to contribute some ideas maybe.

**Q:** And who are some of the other people here who you kind of worked with or exchanged ideas with?

**Ken Waldron:** Oh, Lou Paul was up in the AI lab at the time. And I used the computer up there for my doctoral work so I spent quite a bit of time up there. Let's see, who else, well Vic Scheinman I've already mentioned. And there was a guy by the name of Spalding who I wound up essentially advising him for the year too. I don't know where he wound up. That's about the lot. Salisbury was a bit later, we did – I don't think we overlapped. And I think that's about it.

**Q:** Was there much robotics going on within the AI lab?

**Ken Waldron:** Oh yeah, there was Shakey – oh, not Shakey. The old Rancho Arm that shivered and shook while it was stacking blocks or stuff like that. And that was really the – a lot of the motivation for the Stanford Arm. And then there was the hydraulic arm that Bernie's students put together which was a fearsome beast and terrified everybody. And I remember one

day the guys who were working on that, and I don't remember their names now. One of the hydraulic valves stripped out its mounting screws and flew off and sprayed everybody with hydraulic oil, which of course was a very exciting event. And the thing used to – it was up in that AI lab which was a wood frame building. And this machine was quite heavy and very fast, the computer scientists thought computers are fast so it's got to be fast which was absolutely wrong actually. But anyway, so they hadn't gotten the interface between the mechanical system and the computer right, so every so often the thing would just take off on its own and swing round and that lightweight building would kind of jump off its foundations. So one of the jobs Vic got was to cut a hole in the floor and pour a great big block of concrete to bolt this thing down to. And they put an enclosure around it so nobody could get <laughs> in there. But then they thought, well most of the time it just sits there waiting for the computer to make its mind up. So why don't we build something that's a bit more user friendly. And that's what turned into the Stanford Arm Project. Are you talking to Vic by the way?

**Q:** We talked to Vic.

**Ken Waldron:** All right. So you got the whole story on that.

**Q:** What were some of the discussions at the time here about robotics and some of the possibilities if you can remember?

**Ken Waldron:** I think at the time we were kind of preoccupied with sort of the basics of computer-controlled manipulation. How to get the machine to the position you wanted in some kind of reasonably controlled manner. And how to perform basic manipulation tasks. Things that these days people hardly think twice about, but back then it was a big deal.

**Q:** Why the choice of manipulation?

**Ken Waldron:** Hmm?

**Q:** Why the choice of manipulation as a particular task?

**Ken Waldron:** Well the industry seemed to want that, okay? This was the same period of time when Engelberger was building the first unimates or had recently built it. And that was doing simple industrial tasks like removing molds from die casting machines and stuff like that. And basically it was just an arm that did simple tasks. Well, that's manipulation so that was the initial focus. And as you, I'm sure, know where Vic went on to design the PUMA and some other kinds of manipulators in industry. And so at the time, that was the focus.

**Q:** And what kind of mechanisms were you yourself interested in?

**Ken Waldron:** Oh, back then I was – I suppose I did some theory on these manipulation tasks. Somewhat later I went to Ohio State University and hooked up with Bob McGee and we started, or he had already been doing legged machines and I got involved in that. That machine on the wall behind you was one of the things we did.

**Q:** And so how did you end up in Ohio State?

**Ken Waldron:** Well that's a long story. After I graduated from here I went back to Australia. I was in a faculty position at the University of New South Wales, my wife was also. She is not Australian, she is Indian. And I think she was a little uncomfortable there. We also have a child, our eldest child is deaf and he needed some special education opportunities. So we made the decision to come back to the States. In the meantime we'd done a sabbatical, part of which was spent at the University of Maryland. While there I went and visited one of my old roommates from here, at the University of Houston and discovered I was being interviewed. And so I wound up accepting a faculty position at the University of Houston. After five years there that wasn't working so well and I looked around some and what was available was Ohio State, so that's where I went.

**Q:** And what was the kind of work that you did at Houston?

**Ken Waldron:** I didn't do any robotics there, I don't think. I did mechanism theory work there. That was one of the frustrations there. There wasn't the opportunity.

**Q:** So when you came to Ohio State, Bob McGee was already working on robotics?

**Ken Waldron:** Yes. He'd been doing that – while he was working leg locomotion he'd been doing that since the late '60s, so that was about 10 years before I got there.

**Q:** And how did you get involved in working with Bob McGee?

**Ken Waldron:** I already knew him because I'd met him at robotics conferences overseas actually. And I thought the stuff that he was doing was interesting so when I got there I made a point of going to meet him and one thing led to another from there.

**Q:** What was the first project you worked on together?

**Ken Waldron:** Well I worked some on the old OSU hexapod. I don't think I was ever formally a part of that project but I tried to contribute – well I remember working out, for example, the final inertia ratio on that thing which had Black & Decker drill motors. And a pretty large ratio gearbox between the motor and the joint. So the reflector reflected inertia was huge and I then did an estimate of how much energy the thing was wasting just coming to a halt and reversing

direction every step. And that was about six kilowatts or something. It was pretty impressive. And then when we – when DARPA came to talk to him about doing a big machine, which turned into that thing up there and he needed somebody to look after the mechanical design, it was an easy step to put together a team.

**Q:** And so what was DARPA project about?

**Ken Waldron:** It was basically – the fundamental idea was to build a vehicle for transportation in very rough terrain. And because of the limitations of wheels and tracks in those circumstances they were interested in looking at a legged solution. And we were interested in that so that's what we did.

**Q:** And what year was this?

**Ken Waldron:** That project started in 1981 and it finished up in, I think, 1990.

**Q:** And what were some of the interesting questions and challenges for you in this work?

**Ken Waldron:** I think I could say we reworked all the theory of statically stable locomotion. One of my students, Simon Song and myself particularly did that. This book was basically Simon's doctoral dissertation with an additional chapter added that I wrote myself to provide a general description of the machine.

<off topic conversation about something falling off a desk in interview room>

**Q:** So what was the next big robotics project that you undertook after that?

**Ken Waldron:** Well after that finished – I'm having a hard time remembering. I did some smaller projects. I did come here on sabbatical and was involved with Bernie and Oussama Khatib in what he called The Artisan Project, which was a redundant robot that had series and parallel elements. And in fact I did a design for a parallel wrist for that robot. And Bernie and I and Madhu Raghavan wrote a couple of papers on the kinematics of mixed serial parallel robot configurations, which I think were fairly influential. And so that actually came into the same timeframe as the ASV work. And sometime, it wasn't all that long after that, that – well, I continued to do mobile robot work. Not only legs, but also wheels and tracks. I had become involved in that and produced several student dissertations out of all that. And then I became department chairmen and my research kind of slid for a while. After that I came here, and did some more mobile robot work on joint DARPA and SARIC sponsorship. Did some more legged robot work, part of it was a project that I'd brought from Ohio State on a dynamically stable quadruped, which is still over in my lab there. And subsequently I also did some dynamically stable bipedal work. Those are the major things that I've been involved in.

**Q:** How did you get back to Stanford?

**Ken Waldron:** I had a lot of friends here and I kind of asked Bernie if I could fix up a – basically a soft money position. I'm called, or I was until I retired, called a professor brackets research here which was similar to what we called a senior research scientist at Ohio State. Well as department chairmen at Ohio State I could have fixed a position like that in two weeks. Took eighteen months here, but it happened in the end. And I decided that that's what I wanted to do so I came over.

**Q:** Were there other people, while you were at Ohio State, that you worked with more closely?

**Ken Waldron:** Yes, David Orin, I worked with. Chuck Klein I worked with there. Gary Kinzel [ph?], in my own department. And Necip Berme [ph?], also in my own department. I think there were a couple of people in compute science we worked with occasionally. Bruce Weide was the most active of those.

**Q:** What are some of the major contributions that you feel you've made through developing robots and studying <inaudible>.

**Ken Waldron:** Oh, that takes some thought. Well, obviously the whole thing of statically stable walking machines. I did a lot of stuff on that. Earlier on I did some work which followed on from my doctoral work here on synthesis of planar mechanisms which had nothing to do with robotics but I think was fairly important. Less important but it still impresses people, there's several versions of the Hartenberg & Denavit notation that are used. But the one that is most used was the one that I used in my doctoral dissertation. Again it was before anything to do with robotics. I think in terms of understanding the mechanics of dynamic quadrupedal locomotion, I think we're ahead of anybody else including Marc Raibert. He has had great success in the walking and trotting gaits, which are symmetric and less baffling than a gallop. We have focused on galloping and we still, I would say, don't have a complete understanding. But I think we know more about it than anybody else, still writing papers on that. And I'm sure there was a bunch of other things in between. Did do some of the early work in parallel robotic architectures and I know that's still cited fairly frequently. And with Vijay Kumar who was my student at the time at Ohio State and we did some very basic work on the coordination of multi-limbed systems, which was very widely cited. Of course he's had a very successful career of his own.

**Q:** How would you categorize some of the approaches that you've used to mobility work?

**Ken Waldron:** I beg your pardon?

**Q:** How would you categorize some of the approaches that you used over the years? So are you inspired more mathematically or by logical mechanisms? Is it combinations?

**Ken Waldron:** Well, I think my sort of roots go back to kinematic theory, that's what I first learned about in Australia and which I continued to study when I was here as a doctoral student. But I subsequently became involved in hardware design and I think I was successful at that. And what is now called mechatronics, did a lot of that with the ASV. A lot of it with other systems, even going back to the days of the Stanford Arm, long before it was called mechatronics.

**Q:** How would you say mechatronics relates to robotics?

**Ken Waldron:** I regard robotics as a subset of mechatronics. Mechatronics is integrating computers with mechanical systems of whatever description. A robot of course is such a system but there are other systems that we probably wouldn't call robots which are certainly mechatronic systems, like that thing there.

**Q:** So through your work, have you considered or worked specifically on particular applications of mechanisms that you've designed?

**Ken Waldron:** Well, I have to say that my orientation has always been basic science. So I haven't… Well, I have gotten involved in some applications, but I would say that was fairly peripheral to what I do. I have used biomimetic inspiration of course at various times, certainly with the locomotion work. But you use that to provide inspiration. You don't try to copy nature because we're not good enough to do that.

**Q:** What are some of the organisms that you might have been inspired by for different projects?

**Ken Waldron:** Well when we were doing the ASP, we had a collaborator who took high speed photographs of grasshopper crawling over obstacles and stuff like that. So we studied that a lot. Then we had another collaborator who did experiments with goats, figuring how they manage their legs and how they dealt with obstacles and how they… Those were the main things. And then more recently, of course, Mark Cutkosky works with Bob Full up at Berkeley and uses a whole variety of animals from cockroaches to geckos to whatever. And we interact a little on that. A whole variety of beasties at various times.

**Q:** Who are some other people that you've collaborated with over the years in the US and abroad?

**Ken Waldron:** Former students or…?

**Q:** You can do those too.

**Ken Waldron:** Well, I was the president of IFToMM for eight years. IFToMM is the International Federation for Promotion of Mechanism and Machine Science. I have a whole

bunch of people overseas that I've interacted with fairly intensively. People like Hor Hadge who's maybe on your list of interviewees even though he's in Canada not the US. And people like Adam Moretski who is no longer with us. Jean V'tieu who much earlier passed away who was a very innovative person in the robotics area and did some very important work in France. And Giovanni Bianchi in Italy and several of Moretski's students including Theresa Srilinska. And a bunch of people in France, Philippe Bedeau, Jean Pierre Merlet. And some of my buddies in Australia, Jim Trevelyan was one. Hugh Durrant-Whyte and Gamini Dissanayake who is still a colleague. I spend time each year at the University of Technology in Sidney with him. It's a whole variety of people.

**Q:** And who are some of the students of yours have gone on to work in robotics?

**Ken Waldron:** Well, I mentioned Vijay Kumar who of course has been extremely successful. S.V. Sreenivasan at the University of Texas has been enormously successful in building things like machines to replicate integrated circuits and stuff like that. So I guess he's not really doing robotics per se anymore. Who else? Sunil Agrawal was with me for a Master's degree and then switched to Oussama Khatib for his doctorate and has been highly successful. There's others. A number who have been very successful in industry and… I'm sure if I went down the list I could find some more.

**Q:** Have you done any work with industry?

**Ken Waldron:** Oh, I've done dozens of industry sponsored projects, yes. Still got a little sponsorship from General Motors, for example, which again is not robotics. It's hybrid drivetrains basically, mechatronics fundamentally.

**Q:** Could you tell us a little bit about some of those and what kinds of things industry has been interested in over the years?

**Ken Waldron:** Yeah. Well, some of the industry work was the stuff I did with SAIC, which is basically mobile robots mostly not legged. Mostly wheels and tracks. Then earlier than that I worked with Martin Marietta, aerospace, as they called themselves at the time in Denver. We built a legged robot there, which was for a potential Mars Rover project before NASA changed direction. It changed direction again. But back in the days when they were thinking of fairly ambitious Rover project, the large-sized Rover, we proposed a huge six or seven legged machine for that. And I did most of the mechanical design of that. They actually built a quarter-scale prototype and drove it around the mack blocks up the… I've done some actuation work for industry. That was General Motors again. And that was polymer actuators. Again a mechatronics project, not a robotics project.

**Q:** What other places have you received funding from? You mentioned DARPA.

**Ken Waldron:** Most of my funding has actually been NSF. I think I've had more or less continuous funding from them for many years. And I've also, oh I haven't mentioned any of the Australian stuff. Got some funding from the Australian Research Council there with a colleague at UTS to build a robot to do inspection on steel bridges. And we still argue over whether that's a leg machine or a wheeled machine or what geometry it is. But basically climbing around truss work it'll have legs of some sort. And it will have some adhesion mechanism whether it's electromagnets or something or permanent magnets or something else. Again it's something we're still arguing over.

**Q:** You mentioned that you did a second PhD in Australia.

**Ken Waldron:** No. It wasn't a second PhD. It was a doctor of engineering degree, which is when you submit a compilation of your published work as a thesis and it's examined by a bunch of people around the world. And so that is kind of my ultimate degree.

**Q:** You've been to obviously Stanford multiple times. How has it changed, do you think, over the years the kinds of directions people are taking? The atmosphere?

**Ken Waldron:** Well, back when I was here as a student, you know the design division was very new and unstable, shall we say. A lot of the early faculty either didn't get tenure or didn't stay for other reasons. And Bernie was one of those young junior professors at that time who did stick. And as I say, back then sort of robotics is a very new thing. The AI lab did exist and we've talked a bit about that. I know you've talked to John McCarthy and he was directing that at the time. There was a whole sort of bunch of semi temporary buildings over here that my wife had an office in one of those. She was a PhD student in electrical engineering. And all of that's been bulldozed and replaced by flashy new buildings and things like that. So the campus has changed a lot. The design division has gone from being new and unstable to being very well established and a central part of the mechanical engineering department here. So that's different.

**Q:** What was Bernie Roth like to work with as a student?

**Ken Waldron:** I enjoyed working with him. At the time he was a lousy lecturer. He's since become an excellent lecturer, but at the time he wasn't. I enjoyed working with him. I have to give him credit. He let me do basically a project that I brought with me from Australia on his funding. So that was kind of a unique situation. And actually it was quite a long time after I finished and went my own way that we finally published a paper together. He is not an author on any of my early papers. We're still good friends.

**Q:** What were some of the challenges that working on mechanical design happened over the years and how have they changed? Whether it's from the accumulation of knowledge to technical capabilities that perhaps were lacking.

**Ken Waldron:** The whole set of technologies it's usually called Rapid Prototyping happened relatively recently. That makes an enormous difference. A student now can sit down at a computer and do a solid model and put the model through a laser cam or something and build parts in a very short period of time. It's so much easier to build prototype hardware. So we can think about building lots of prototypes to try out ideas and things, which you simply didn't do back when building a prototype was enormously expensive and required lots of time. So all of that's different. You have to change the way you think because back when I was a student, you wouldn't think of building anything unless you had a really big grant to pay for all the costs. Now you kind of don't do anything without thinking of building hardware.

**Q:** What were some of the challenges of the parallel risk that you described or some of the hybrid systems?

**Ken Waldron:** Well, at the time nobody had really thought about the kinematic equations for those things and how you would control them. Because you see the way the mathematics works for a parallel system is fundamentally different from the way the mathematics for a serial system. And what's easy in a serial system is difficult in a parallel system and vice versa. So putting them together in trying to run a system that had both features at the time was something that nobody had explored. So we had to roll up our sleeves and, I think, do some pretty fundamental stuff to just work out how you would indeed do that.

**Q:** And what do you think are some of the outstanding challenges or kind of questions that are important to ask in the next five to ten years.

**Ken Waldron:** Oh, where to start? There's so many of them, really. The one that always frustrates me is actuation. And I've done quite a few projects myself trying to improve that. But fundamentally things like electric motors are rotten. If you compare them to what we can do with biologically, they're pathetic. Yeah, hydraulic actuators are much stronger and very quick and all that, but they have a whole bunch of problems themselves including being very wasteful of energy. And when you think about it, a muscle fiber converts chemical to mechanical energy in a micromechanical package. And we can't even remotely approach that. Our usual way of converting chemical to mechanical energy after all is a heat engine. And so there's enormous scope for things that we can't yet do. The whole thing of human interactive robotics, which I know is a very hot area right now, but we're not very good at that. There's someone that does very fine stuff over there essentially making the mechanical system so that if it whaps you it won't kill you. It'll hurt. But maybe you don't have to fence the robot off. But really what's missing is the massively parallel sensing that we have and the ability to process all that information. If you had that you probably wouldn't need to make the robot soft. It would be smart enough not to do it and do things that would damage people. But we're light-years away from that one. There's going to be a lot of government funding and a lot of research effort go into that. We'll see what happens. I think we've got a long, long way to go.

**Q:** What are some of the breakthroughs that you've witness over the years?

**Ken Waldron:** Well, the first and biggest was simply the integration of computers with mechanical systems, which changed the landscape enormously. Before that you thought in terms of building a machine with a single big motor, turning and it coordinating everything mechanically. And nowadays the game is you individually actuate joints and coordinate them in software. That's a totally different way of doing things. So that was important. I've already mentioned the rapid prototyping development. And of course computer aided engineering of all sorts all happened during my career, so that was a vast change also. Back when I was doing my doctorate, you did a lot of graphical computation. That was very rapidly taken over by computer aided design type software. And it was in fact a very interesting problem learning to use that because the best ways to do things in the computer are not the same as the best ways to do them with a pencil and paper.

**Q:** Did you ever run into Ruzena Bajcsy when you were here?

**Ken Waldron:** Oh yeah, I knew Ruzena quite well. Not here. I knew her at UPENN and of course subsequently at Berkeley.

**Q:** Did you ever collaborate on anything with her?

**Ken Waldron:** Not really. We did talk a lot for a while. And of course she hired Vijay. There was a fair bit of conversation, but I don't think any formal collaboration.

**Q:** What was that conversation about? What kinds of things were you talking about?

**Ken Waldron:** Of course she is more of a perception person. I'm a mechanical system guy. And she was at the time interested in bolstering the ability of her lab to do mechanical things. And Vijay was one person who early on helped with that. Lou Paul of course was there at the time, but he'd gone to the Dean's office and was not doubt busy with other things. Xiaoping Yun whose now at Naval Post Graduate School at Monterey was there early on and working with her. I knew all those people and talked to them. That's about as far as it went.

**Q:** If you had some advice for young people who might be interested in robotics, particularly in design, what would it be?

**Ken Waldron:** I think robotics has always been kind of a difficult animal to deal with because it does involve so many different technologies in an integrated way. What I advise my own students to do here is to take all the mechatronics courses they can get hold of and there is a good series here. And then to do the basic robotics core sequence to get the fundamental mathematics and stuff. And there's also, we have good computer vision courses, which I would advise them

to do. The world's changing. I'm not sure I can tell them what to expect beyond a year or two after they graduate.

**Q:** What was Vijay like as a student?

**Ken Waldron:** Oh Vijay was wonderful. I didn't work with him like a student. I worked with him like a colleague. I suppose I put the problems before him, but he'd go away and come back with a solution kind of that. He was fun.

**Q:** Are there any other stories that you'd like to share?

**Ken Waldron:** There have been other very good students too. Jim Schmiedeler who's now at Notre Dame was another student like that who was great fun to work with. More recently, Alex Perkins who is now at Boston Dynamics. And Paul Zonker who's about to graduate have all been very fun people to work with.

**Q:** This is all we have unless you have something you'd like to add.

**Ken Waldron:** No. I think I'm about bled dry.