Interview with Michel Maharbiz

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"“I hate to break it to you, but you are a machine."

Michel Maharbiz, an associate professor of Electrical Engineering and Computer Sciences (EECS) at UC Berkeley, has pushed his lab to the frontier of biological interface technologies and is increasingly interested in applications in synthetic biology. He received his B.S. in EECS from Cornell University in 1997 and his Ph.D. from UC Berkeley in 2003 under Dr. Jay Keasling for his work on microbioreactor systems. Maharbiz's lab has gained public recognition for their work on controlling the flight of insects by building so-called "cyborg beetles." Though it is only one of many projects pursued by him and his co-investigators, it speaks clearly to his vision of a new era of technology: one that uses bio-interfaces with technology to harness nature's complexity. MIT's Technology Review named the cyborg beetle one of the top ten emerging technologies of 2009 and TIME magazine similarly hailed it as among the top fifty inventions that same year. Berkeley Scientific Journal met with Professor Maharbiz in 2011 to learn about his research and to explore his ideas for the future of science.

BSJ: Our theme right now is Science Fiction and a lot of your projects do fit into that theme of pushing the boundaries back. The first one we have to touch on is about the cyborg beetles. Can you explain what that project is and what you are trying to do with that?

Maharbiz: The cyborg beetle project was a DARPA funded project started by a professor at Cornell named Amit Lal and he wanted to know if technology – and by that I mean electronics, mostly – had miniaturized sufficiently and enough was known about insect neurophysiology to be able to usefully affect, or control, the flight of insects. This was by no means the first time this idea has been thought of or discussed. This has been in the area of people who think about insect neurophysiology and flight dynamics and it's been floating around for some time. The government has a long history of attempting to do things with insects and this was the latest version that was very well funded. We set out to participate in that project and we chose to work with beetles, not with moths, grasshoppers or locusts, because while beetles are not one of the most studied animals, their flight systems have useful similarities with flies, which are very well studied.

The two most studied insects, in terms of neurophysiology and flight, in recent times are flies and moths – those are the model insects. The problem was that moths were distinct from flies in flight for some technical reasons we did not like and moreover, they didn't carry much stuff. It is kind of hard to get a moth to carry more than a gram. Beetles have flight mechanics and neurophysiology that are actually close enough to flies to be interesting and there are more species of beetles than anything else on the planet. They're in almost every microclimate around. In fact, there's a professor in Hawaii who studies them and you can find them almost from the top of Mauna Kea above the tree line to down near the ocean and watersheds. He studies how these beetles have changed in their conditions. They can also get very big, so you can get very large beetles and you can Google it and see for yourself. We did some of these interventions for a beetle called Megasoma elephas a couple of years ago and that is a 30-gram beetle and it sounds like a helicopter when it flies. It makes it a lot easier to put stuff on it.

Now, I'm primarily a gadget builder, so for us, we were primarily coming from the competence of knowing a lot about the technology and the gadgetry and being very good at it, and that's what gave us an edge. We also took the neurophysiology very seriously. Even though we certainly are not in that field, we became like students of the field – we read all the papers obsessively and Hiro, that is Hirotaka Sato, who's now a professor in Singapore and was my post-doc who did most of the work on this project, and has become an expert. He apprenticed with one of the last generation's premier insect anatomists, Professor Kazuo Ikeda down in Los Angeles, and it was like boot camp; he would fly down there and train, like: "You have become the best". They're both Japanese, so I can just imagine that conversation actually happening.

BSJ: Just imagine them saying: "You are the beetle master!"

Maharbiz: (laughs) Yeah! Something like: "You have dissected a beetle with your pinky." So, he's become an expert, so much so that just recently a couple months ago, he gave a talk at a physiology conference where he detailed his latest work. It's not published yet, but he found that one of the muscles that for close to a hundred years had been thought to just fold the wing in when the insect was done flying in fact has a flight role. That was not obvious and it was cool that all the people there were leading insect neurophysiologists. One famous guy was like: "Loved it!" It was a very long road to do this though. You got to really want to do it. Part of the reason we succeeded so well is that I knew how to build the gadgets and Hiro is a chemist, so he has a solid foundational training in scientific method. We knew how to build the gadgets and we took the biology very seriously. We didn't just go, "Oh well, whatever," like a lot of people who can be very flippant when they are in one field looking at another. Anyway, so that's what we did. We miniaturized the package so that it had a radio and all that stuff, including neurostimulators, and we found the right places in the brain and muscles where we could stimulate to get desired effects, including turning on and off the flight, modulating the wing envelope and actually getting turns. That's what that project was about – it was about whether we could screw with the flight of an insect in a meaningful way – and we showed that you could, but there's a lot of work to be done. Just because you can get it to broadly turn left and right doesn't mean you can fly it like an F-16.

There is a level of control that requires a lot of work to be done, but having said that, let me take a step back and add another thing: the jury is still out on whether it is a good idea to use an insect as a flight robot. The reason goes back to something that Robert Full here in Integrative Biology is fond of saying. I really like his work and he'll tell you that these insects did not evolve to be your robots; they are actual animals and that means that hidden both in the physiology of the insect and what it does, its mechanisms, and even down into the genes, there is the detritus of the evolutionary history of the insect. It has all this other stuff in there and so the insect isn't likely to be the greatest robot because it has all these other things it wants to be doing that you may or may not be aware of. The jury is still out on whether we will be able to really exert the appropriate amount of control pressure to get what we want in an efficient way. I personally think we can.

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At the moment, it still looks attractive because while inevitably, there's no doubt that people will start to build miniaturized flight robots – they're working on it right now, Rob Wood at Harvard and Mike Dickenson at the University of Washington have looked at this for a long time, and Ron Fearing here has been building them – there are still some severe technological limitations. Especially with power: it is really hard to provide enough power for these things to fly for very long periods of time. If you look at the DARPA hummingbird, which just came out a few months ago, it is a little robot hummingbird. It's beautiful, but it's not going to fly for very long – I think it flies for 5 or 10 minutes. At the moment, it's still attractive to try to do this. Now, having said all that, I've never been into it really because I want to build a microvehicle. I am really into it because I am interested in the idea of merging the synthetic and the organic: that's the reason I do it. I think this is a really cool playpen test bed for looking at how these synthetic and organic controls can work with each other to do something interesting and I think the future is

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going to have a lot of integrated things between what we think of as organisms and what we do not.

One of my other post-docs will publish later this semester to show how you can implant recording interfaces, very thin polymer recording interfaces, before the eye grows in the insect during pupation, inside the imaginal disc of the insect. What will happen is the eye will grow into this interface so that when the thing is worn, there's a normal eye and coming out of it is a wire polymer substrate from which you can record the insect eye's neural signals. You cannot separate those things when this is done, they grew together; you can twirl it by the damn interface. That whole idea of building interfaces to multicellular stuff is really what my lab is all about. That is why I picked this. I almost, I would not go so far as to say, but I almost do not care whether insects are useful as flight robots. (laughs)

BSJ: Going off that merging, a lot of this is tissue interfaces right? Where you can put things in and make it work with the biology rather than against or simulating it?

Maharbiz: Yeah, exactly.

BSJ: The other project we saw was where you are trying to make a synthetic leaf. We thought that was really cool – you're trying to harness that complexity rather than emulate it fully, right?

Maharbiz: Yeah, I mean, basically what we are trying to see is if – this is another crazy idea, my lab is full of crazy ideas – but it is looking like it's working. We want to essentially find a low-cost, easy to make – I mean, my dream is to put it in MAKE magazine, so I would love to put it there and have anybody make it – leaf-like evaporator essentially as little bushes. During the day, water will evaporate and at night, just like a leaf, water will condense and this cycle will repeat forever as long as there is normal weather and there is a reasonable cycling of the humidity and a temperature-humidity gradient. I have this crazy notion that you can extract power from the fluid flow as this happens. It will be evaporation and condensation, so it'll be very low power, but it will be infinite as long as the planet is doing this. I'm mostly doing it because I am curious about the fundamental principles of it. I want to know how I would actually build one of these things. I'm really fascinated with the physics of how you can build these massive water-pumping systems. Have you ever wondered? A redwood tree does not have a pump and yet it sucks water all the way to the top. The physics behind it is just awesome, and the fluid flows you can get in those big trees are actually kind of sick! That is actually two projects in one.

One is building these leaves, which is actually being done all by an undergraduate – he is a physics major and he's doing very well. Maybe when he gets a little farther, he can talk to you guys. He's been building these leaves with these porous materials into which he molds vascular channels just like you would see in leaves and he's basically trying to get the best technology you can to do this.

The side project that we published and gave a talk on in the summer we published in a paper the Transducers 2011 conference. To my knowledge, we have the smallest Tesla turbine, which is an old idea that Nikola Tesla came up with. It's a way of extracting power efficiently from very low-pressure flows. What we think we can do is build a Tesla that will sit in the stem of this little bush and the bush will still there an evaporate water and turn the Tesla and you would have to do absolutely nothing else. It would be like a water mill inside a plant, except the plant is a fake plant. We'll see.

BSJ: How did you actually get into research? We were reading your "musings" that you have posted on your website.

laughter

Maharbiz: I don't want to have a blog, because that takes too much time, so this is my loser blog. No one can actually respond.

laughter

BSJ: Whenever an undergrad wants to apply to your lab, he'll find the musings.

Maharbiz: Oh yeah. I have infinite confidence. I'm 35, right, so anyone under 25 or 26 can find any of this shit without thinking. The problem that I have is with old people because the old guys can just never find it. I never have to try, because if you are young, like you guys, you breathe this shit. You are like "oh, I don't know this, well, Google'll tell me." It's just the 50-year-old guys who can't find anything.

laughter

BSJ: So even at 35, you're getting into more complicated – or better put, more futuristic – ideas. In the musings, it says that in 5, 10, 100 years, everything will be a bio-interface.

Maharbiz: Yeah, I'm obsessed with that – I think that's true. I think that touches on another area that I'm trying to get into. My advisor was Jay Keasling, so he's a big synthetic biologist, and I'm trying to get my group to steer a little more in that direction. This idea touches a lot on synthetic biology. I think that we will begin to figure out how to reprogram cells, effectively, to start building stuff – not for even medical reasons, though of course that will be a huge driver – but just as a way of engineering things. When we start to do that easily, in the sense that you can program it like you can program circuits now, the world will very quickly change to a place where a lot of the things that you think of as dumb or inert, like this table, will in fact be loosely descended from cell lines. They will have a different meaning in my mind. I don't think I will have made a table out of kidney cells; I think that the idea of these cells as the fundamental building block of machines is a very powerful idea. There are more machines on the planet built with nature's technology than with ours, even if you count every transistor as a machine. Something like this table will probably be able to use whatever light there is, or humidity and moisture, and essentially program itself. You could program it or it could program itself – it will heal, build things. I think that organic future where we fuse two sides of it, the synthetic and the organic, is inevitable and it is going to be a huge part of our technology. Maybe when your children start to have children, or some people say faster, but at least then to be pessimistic.

This isn't like "everything will turn into biology" because there is all sorts of shit that biology never came up with that we are very good at. Biology and nature did not build electromagnetic radios, turbines, the wheel or rotary bearings. We have a huge palette of technology that we've generated ourselves and by no means are we going to turn into Tolkien elves and go live in the forest, but I think that the extra palette that nature will bring to the table will just change a lot of things in everyday life. I believe that this is true so I basically am trying to carve a path to do stuff in that area.

BSJ: Do you think that these new technologies will be effective? Because you said you had to battle some of the detritus genetically, how do you expect to counteract those since the cell is extremely inefficient?

Maharbiz: There's two really cool sides to that: one is macro and the other is micro. Let me add that I'm by no means the first to say this – Drew Endy and Tom Knight at MIT, Adam Arkin here, and Jay [Keasling] have all been saying this stuff for years. Let me answer this in two different ways. I think in the long run, the question of, say, genetic detritus or other things in these cells, will be made moot by the fact that already, people are trying to build completely synthetic cells from the ground up, you know, the Craig Venter effort that recently rebooted a cell from a synthetic base. Those efforts will only get more sophisticated. It is inevitable. It's inevitable that at some point, we will have something that is a cell unto which over the years people will add more and more diversity and pieces to, developing progenies like "this is an adherent cell" and so on. In that way, we will largely avoid that problem. I'm not claiming that necessarily that the ultimate goal of this futuristic vision I am giving you is to have E. coli doing stuff or, like I said, kidney cells making tables. It'll be something loosely derived from it in a sense that it'll be like a distant cousin, only in that it uses the same general motif of cellularity and probably similar molecular machinery – enzymes and proteins and genetic code of some kind. Of course, the farther out you want to extrapolate, the more mumbo-jumbo this becomes and I could eventually just tell you any story I want. The limit as I go out far enough is that I can tell you anything. (laughs) In the short run, it's a huge problem. The devil of synthetic biology is that you want to get E. coli to do something because it is an attractive experimental system, but E. coli has like 900,000 other things that it is doing lots of times.

If you think about it crassly as a computer, you are trying to get the computer to run the little bit of code you put in there, but at the same time that computer is connected to a giant internet whose protocols you do not understand and is running 100,000 other threads. You are always upset because it's not quite doing what you want because it is doing other things. In a sense, you can think of biology this way. You know nothing about computers whatsoever and you are presented with the Internet in the sense that you are presented with thousands and thousands of computers. You don't know what they are, you are just given this thing with a screen and keyboard, a cable that plugs into a whole bunch of things and you don't know what any of this shit does. You are told to figure out how it works and you spend 250, 300 years or more banging away trying to press different keys to see what different things come up on the screen and sending a signal. Eventually, you realize that the cable coming out of the back of it allows it to talk to other computers and you start to figure out how it talks and sends stuff. That is essentially what biology is: reverse engineering a complex system. At the moment, we have not built one from scratch, we just go and find all sorts of computers in this space, E. coli, whatever, and we try to run some code on it, but the computer is currently running a word processer and five games and is being pinged. So you know, this is the problem when you are trying to do something in a very noisy environment. So yes, that is going to be a problem, but I think it will be solved.

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I think there is another kind of interesting, sort of cool part to all of this that's even more woo-hoo (whistles) but I like it because it is very environmental. I think that there's a weird little corollary to what happens if we start to move our technology to an organic base of some kind. If we are building things out of things that are derived from cells and have that sort of motif, it will probably allow us to build manufacturing systems or just technological infrastructure that is very tightly wound into the local ecology. So that means that both the control loop into the local natural system is a lot faster and also a lot more dangerous because right now, when you run a computer virus, it doesn't kill all the trees in Berkeley. That is something new, just to sit there and think: "I am writing some code and by mistake wipe out half the raccoon population and every time a grad student accidently miscompiles something, some pigeons get a virus." The flip side of that, and this is very futuristic to think about, is that I think that when you have well-run machinery that runs this way, you have much less of the problems that you had in the Industrial Revolution where you built up these giant steel factories that would take in all these purified things and spit out all these products and in the process spew crap into the air and pollute the rivers. That is because none of the machinery understands the language of the things around it; it is just an alien technology that has been dropped there. I mean: it is what it is. Industrial age factories are alien technology that dropped in on the technology that existed on this planet for a billion years and started going ape-shit and ripping it up and throwing stuff out there that the other technology did not understand. What does a tree know about a sofa? You needed to pulverize half an acre and purify all these chemicals and spew all this stuff into the air just to produce that thing. You just suddenly had a different technology that doesn't talk to the first one. If you can merge back a little bit to it, it becomes much more integrated.

BSJ: One thing that there was at the very tail end of one of the musings was your ethical considerations. It did go along that idea of if someone vaguely messes with our technological side, like the end that we have made, it ends up affecting the end that was more natural. We are already playing with the environment and our relationship with the environment is very close now, in the sense that we are able to affect change very quickly and there is a big change, like if we build a factory. This would close the gap between our technology and the effect it would cause to the environment.

Maharbiz: In my mind it would, yes, but in my mind, this is one of the benefits actually if this is properly done. It allows you to understand the ecological consequences of it and it has a very nice, very powerful ecological story to it. I think that it something that is beginning to be discussed by people, but in the end, it's just so early that this is all just futurism right now. If you start to think off far enough, it does have a beautiful ecological consequence that it forces us to become real stewards of the technology base we came up with. I hate to break it to you, right, but you are machines. There is a technological base that fabricated you that we tend not to be very good at understanding. We bitch when our Intel makes three little errors on its math coprocessor – think about how much less we know about the technology that built you two or me.

BSJ: It would magnify our potential impact on the natural world.

BSJ

Maharbiz: Yes, but there's no way around that, man! This is the thing, people, you know? There is already 10 billion of us on the planet around the corner, like, what're you going to do? You got to grow up; this is the thing that drives me crazy about these arguments. Yes, we can annihilate ourselves and wipe ourselves off the planet. So be it. I have two kids and I want them to have it, but that is where we are. You cannot pretend. You cannot go back to a sylvan lifestyle with like a million people on the planet unless you are a serial mass murderer. We are here – you got to do it! Right now, we just have to look for the ways forward and hope that we are a mature enough species that we will not annihilate ourselves in the process, but there is no way back and no way not to do this. Whatever this ends up being, your generation is going to embark on it. It is a very serious thing, this argument that people bring up: "oh no, you're messing with it." What do you mean, like, what else do you propose? You cannot sustain the population of the planet and you cannot control it. First of all, let us start with whether you can stop it from growing tomorrow – no, for both ethical and practical reasons, it is impossible. So next thing you can do is say that each of those individuals and family units are not assholes. That is essentially what the environmental movement falls down to. Within economic reasonability, make sure people are doing the best job they can and are not being assholes to the technology base that they came from. In the first world, in many cases, that is starting to take hold pretty well. In the third world, there are very serious constraints to that. I mean, it is all very well and good for all of us who are well fed and fairly well off to have these discussions. None of that changes the basic fact that the population is growing and our needs are growing; our energy needs, even if we decide to be green tomorrow, are substantial. It forces us to be stewards. Whether that is any of this mumbo-jumbo or better wind turbines or whatever, we can only go forward and figure this out.

BSJ: Do you think the definition of what we consider "alive" must change as technology changes?

Maharbiz: Yeah, definitely. I think "alive" is meaningless.

BSJ: Currently, the debate on "alive" is stuck on viruses and prions.

Maharbiz: I think the concept and definition of life is something that is a holdover from the vitalism of Western European thought from a few hundred years ago. I think that is just not very well defined and all you have is a spectrum of computational complexity – that is all you have. That doesn't mean, by the way, that there are not points where those computers become capable of sophisticated models of pain so that you have to start worrying about not inflicting harm on them. It doesn't mean that they are not capable of self-determination and accountability and all those things. Those are almost philosophical questions that I cannot answer. There is a very beautiful 5,000-year-old discussion going on about that. Calling it computational systems does not remove any of the onuses on an individual on behaving ethically and responsibly with regards to the computational system. Here is an example. We do not feel really bad about throwing bleach into a sink, which is killing things, organisms obviously, but we maybe feel bad sometimes swatting a fly, maybe you don't know why. You certainly feel bad about taking an ax and chopping off a bunny's head. That is the Disney effect, and you probably feel really horrible shooting another human being, or ax-murdering him or making him feel bad or giving him pain by taking their arm and ripping it. There is a whole lot of nuanced issues that go on there, but one of the issues that comes into play is that we believe – we have good evidence for, but it is not conclusive – that there is a point in the scale of computational complexity where the organism is capable of producing fairly robust models of pain and particularly can predict pain, can associate pain, and can fear it. Fear requires you to be able to think about it, imagine it, have a meta-version of it and expect it and know what it brings and these sorts of things. You don't feel bad for your iPhone, right? Your iPhone has sensors. I mean, I could write a little app right now, and I was almost tempted to do it, that goes "ow, ow, ow, ow" every time I shake my iPhone. It would go "ow, stop, ow ow, that hurts, stop it, ow" but you wouldn't feel bad for it, so why don't you feel bad for your iPhone?

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BSJ: Because you assume it doesn't actually feel that pain.

Maharbiz: But what does "feel" mean? That's the question, what does "feel" mean? I mean, if I take an insect and go like this (pushes finger on table) and you see its legs wiggling more as I whack the shit out of it, would you feel bad?

BSJ: Yes.

Maharbiz: Why?

BSJ: Because we assume it's also a biological organism and can feel pain. When we feel pain, it's a feeling.

Maharbiz: So what is interesting is that you said that part of the reason is because you feel it is a biological organism and those entitled to a special category of description. It's a sort of self-recognition thing, part of this giant family of things that I belong to. What if I built a robot that had all the same sensors and started (punches the air). Would you feel bad about the robot? Like, if you had a robot dog and a real dog, would you feel bad blowing the shit out of the robot? You would probably feel bad about blowing the dog away with a 12-guage shotgun but probably not the robot. A lot of this has to do with a lot of the way we perceive it and the reason I am telling you all these examples is because yes, the line will be blurred and we will be forced to realize that all there is on this planet is a spectrum of computational complexity. That computational complexity sometimes arises out of things that we consider discrete organisms and other times arises from other things we do no consider discrete organisms. You should read a book, an old book now but it is beautiful, called "Gödel Escher, Bach." Have you read it, by [Douglas] Hofstadter?

BSJ: We've heard of it.

Maharbiz: You should read it! It is an older book, it doesn't matter whether everything he said in there was right or wrong. It's that he has very elegant analogies, for example, an anthill. It's pretty easy to demonstrate that an anthill computes – that it makes a collective decision and that it's not the ants that are doing anything. It is actually the anthill. So in that case, the computational complexity comes out of the anthill, not the individual ant. These kind of things, and there are sorts of things with a lot of computation going on, in my opinion, in ecological

BSJ