Catalyzing Computing Podcast Episode 31 – Autonomous Flight and Landing on Mars with Behçet Açikmeşe (Part 1)

The transcript below is lightly edited for readability. Listen to "Autonomous Flight and Landing on Mars with Behçet Açikmeşe (Part 1)" here.

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[Intro - 00:10]

Khari: Hello, I'm your host, Khari Douglas, and welcome to Catalyzing Computing, the official podcast of the Computing Community Consortium. The Computing Community Consortium, or CCC for short, is a programmatic committee of the Computing Research Association. The mission of the CCC is to catalyze the computing research community and enable the pursuit of innovative, high-impact research.

In this episode of the podcast, I interview Dr. Behçet Açikmeşe. Behçet was a technologist and a senior member of the Guidance and Control Analysis Group at the NASA Jet Propulsion Laboratory, from 2003 to 2012, where he developed guidance, control, and estimation algorithms for formation flying spacecraft and distributed network systems; proximity operations around asteroids and comets;

and planetary landing. He is currently a professor in [Aeronautics and Astronautics], as well as [Electrical and Computer Engineering] at the [University of Washington]. He's also a member of their [Autonomous Controls Lab]. In this episode, Dr. Açikmeşe discusses his time at the Jet Propulsion Laboratory and what it takes to land a rover on Mars. Enjoy.

[Background and Joining NASA's Jet Propulsion Laboratory - 01:23]

Khari: Here today with Behçet Açikmeşe is a professor at the University of Washington. How are you doing today?

Behçet: I'm doing good. Thank you for inviting me, Khari. How about you?

Khari: I'm doing pretty well, all things considered. So let's dive into it. Where did you grow up and how did you get involved with engineering and computer science?

Behçet: I grew up in Turkey. I was born and raised there. I did my primary school education, middle, and high school there, and I went to college in Turkey. After college I had the opportunity for a fellowship and to come to the United States to pursue my graduate school career. I came to Purdue University during my Master's and I studied computational fluid dynamics.

Again, my undergrad degree was in engineering and my graduate degrees as well. The area that I did my Master's in was computational fluid dynamics. Then I did my Ph.D. in control theory. Control theory is a quite mathematical area, that's what attracted me to control theory, where I could use advanced mathematics for solving engineering problems. It's an area that's unique in that you can apply mathematics on real physical systems. For example, computer science is mostly about developing algorithms that you interact with via a computer, via your laptop or whatnot. Or you interact with them when you go to the bank, you interact with the ATM machine, for example. But in control theory, the algorithms that you develop interact with physical systems without you being in the loop. So that's really what attracted me to have a solid mathematical basis to develop algorithms and to use those algorithms on physical systems. That was really attractive to me. so that's how I got involved in control theory I guess.

Khari: I know you spent about ten years of your career at the NASA Jet Propulsion Laboratory. Can you tell me a little bit about that experience? What is JPL and how did you end up there?

Behçet: After my Ph.D. — my Ph.D. was in control theory but my advisor was in the aerospace engineering department, so I got my Ph.D. degree from aerospace and that's where I was introduced to some of the applications of control theory in aerospace — I interviewed with JPL and I got an offer. That was one of the happiest days of my life. So I moved to JPL from Purdue University.

JPL is a NASA R&D lab, research and development lab, that's located in Pasadena, California. It is not a usual NASA center like Johnson Space Center. It's called an FFRDC, Federally Funded Research and Development Center. So it has a different status, but JPL is very well known for robotic exploration of space — that's the role of JPL. Its main purpose is to develop spacecraft and the instruments on the spacecraft to go to other planets in the solar system, Mars and other places; but it also operates spacecraft beyond the solar system.

It does a lot of what I would call the robotics part of the mission, the robotics missions of NASA. And the group that I joined at JPL was responsible for developing algorithms, control algorithms, that are used onboard spacecraft, both for deep space missions — missions that do not go to planets, but have other purposes, like they look at stars, they are telescopes and whatnot — as well as missions that end up on other planets, typically on Mars. JPL is very well known for those missions. For example, a recent one is MSL, Mars Science Lab. It has been almost eight years now since JPL landed the rover Curiosity on August 5th, 2012.

I had a key role in that mission, that's why I am intimately familiar with that mission. But JPL has plenty of these missions — before that it was MER, Mars Exploration Rovers, in 2004 I believe. So, you know, it's one of the one of the major centers of NASA.

[Landing a Rover on Mars - 6:00]

Khari: You worked on a project sending the rover to Mars. What are the challenges to sending spacecraft to Mars from an engineering and computer science perspective?

Behçet: I mean, there are, of course, a multitude of challenges. I'm intimately familiar with a group of challenges, but I probably will ignore some of the others because of my lack of insight into some other parts of the mission.

It's a very complicated mission. For example, Mars Science Lab — I'm taking that one as an example — is maybe the mission with the most autonomous capability on board to date, in terms of planetary landing. That's why it's a historical mission. Not only because it landed the Curiosity rover, but it's because of engineering reasons. The system was completely new, the hardware was new, a lot of algorithms were new. So, you know, it was in that way it was their flagship mission, and it's a good example.

One of the biggest challenges from a controls perspective is the need for autonomy. You cannot control a mission that will land on Mars in the critical phase of the landing, which is the entry/descent and the landing phase. These missions have a long phase before they even get to Mars. There's the interplanetary cruise where you leave earth and you try to go to Mars. It takes about eight months if I'm not misremembering.

Of course, there are things done during that time. Again, we are not just sitting there and waiting, but there are a lot of opportunities to interact with the spacecraft. You send information, you receive back, you may correct some decisions and such. So even though none of these things are trivial, these things have been done before and there is quite a bit of involvement in control of the spacecraft. But once you enter the atmosphere of Mars and make the decision to land — “OK, we are going in” — it takes about seven minutes or so. That's why they informally call this space the seven minutes of terror. There’s a very nice video online if you want to watch it. It’s made by JPL. [link to video here]

Once you enter you have seven minutes to land. But sending information back and forth to Mars takes about 24 to 26 minutes, if I'm not misremembering. So it's impossible to interact with the spacecraft during landing. Once you realize that it decided to land and enter the Martian atmosphere, it already landed basically. You’re just getting the information late.

[Laughter]

There's nothing that you can do after that point, everything is over pretty much. So this phase has to be done autonomously and that's a major challenge from a controls perspective. You have to make a lot of decisions onboard based on sensing and sense data — we have onboard sensors that give us information about the state of the spacecraft and where it is, what it is doing, its orientation, many other things like its velocity and such.

By using this information, we make onboard decisions on how to control our actuators. We have thrusters, we may have other actuators as well, so that the spacecraft does the right thing to land. And the algorithms that are onboard to process the sensor information and determine the actions that we have to take are designed in the group that I was a part of. I was one of the key engineers to design one of the algorithms — there are several algorithms that helped land the Curiosity.

There is a set of algorithms during the entry phase: when you enter the atmosphere you are trying to slow down by using atmospheric friction; then we open a parachute and we slow down a bit more. We remove the parachute at one point because that's not enough either. The Martian atmosphere is not very dense. It's like, on average, one percent of the density of Earth. So now you have to slow down by using your rockets. You may see people coming back to Earth from space and you typically see the parachutes landing them softly in the water or sometimes in the desert. That doesn't happen on Mars. We don't have that kind of air density to slow us down, so we have to use rockets. That's where everything becomes very, very tricky. You can imagine people spending an enormous amount of time to even make sure the rockets will ignite after eight months in the cold environment of space.

[Laughter]

You are entering. suddenly they have to open their eyes up and start the engines. All these processes have all kinds of risks, both from a hardware perspective, as well as the software that controls all these processes. So you are protecting yourself against all kinds of faults, and after you do that you are protecting yourself against all kinds of environmental variations because you land on the planet and there may be winds, there may be dust storms that may fool your devices, and so on. There can be a bunch of things that can go wrong and protecting yourself against all those things, some of them with respect to the spacecraft, some with respect to the environment, is a difficult game.

We try to anticipate all these factors, and develop algorithms that can handle all these variations that you may see and perform well despite all these variations because we don't know exactly. And handling all this uncertainty is a part of a controls engineer's job, that's our major job — using sensor information such that we can protect the spacecraft's motion by taking the right actions so that it safely lands on Mars.

Again, in terms of software, anticipating all this complexity and writing the software that handles all this complexity is the major challenge. In terms of hardware, you can imagine there are many challenges too — you are going from Earth, to space, to Mars, all different environments, different temperatures, and so on. All these things have a strain on the vehicle and hardware on the vehicle must handle this. So it's full of challenges.

The other major challenge, the more important challenge is that you have one shot and there is no coming back from that shot. There is no recovery. The first time you test this system in full is when you are executing the mission. There is no other way. So all these factors are really making it a high stakes engineering design. For example, if you design a car you can test it, you can find issues while testing, that is done routinely. We do that for a spacecraft of this magnitude, too, but you can't test everything. For a car you can test more or less everything, but here we just don't have the environment to test it in the right way. When you are entering Mars, those are speeds you cannot replicate.

[Laughter]

You cannot replicate the actual conditions, so what you are doing is a lot of well-informed guesses about what will happen, models if you like. And based on that you have to put your arms around the problem and make sure that you took all the precautions for the successful execution of the mission. I'm just giving you this sense of how complex this is, you know.

Khari: Yeah.

Behçet: And when it succeeds is a major, major relief and success.

Khari: That sounds very difficult. Have there been any major failures of attempts to land rovers on Mars?

Behçet: Oh, yeah. Other than the U.S. nobody has succeeded. They have attempted, but nobody has succeeded. I think more than 50 percent of missions have failed. It's almost 50/50, and other nations have failed all the time, so that they have a 100 percent failure rate as far as I know.

That means it's a difficult thing to do engineering-wise. We have been really successful. JPL in particular has been really successful with missions starting in the 90s. They have also had their misfortunes. That's why it's a very, very risky business. Of course, there's taxpayers' money involved. You know, it's all a taxpayer funded effort. We learn a lot, we gain a lot of capabilities, but there's a lot of risk in that way, too. I'm glad the public supports all these activities. People work really, really hard to make sure that those sacrifices are met with proper, high quality engineering.

Khari: So most of those failures, do they typically occur in the landing stage, or is it getting to Mars itself, or...

Behçet: Typically in the last stages, either entry or landing, somewhere in there, because that's when...You know we have sent probes to different planets, asteroids, comets, outer space — of course, those involve risks too, but when you compare with entering the atmosphere of Mars and landing on Mars, I think that's an order of magnitude harder. That's why failures typically happen: when you're in close proximity of Mars, when you enter the atmosphere. So, yeah, I can say with a level of confidence that is typically when you are close to Mars

Khari: Do you know what the speed of an object is on entry?

Behçet: Oh, I knew that, but let me check. I think it was over 25,000 kilometers per hour, but let me check. That’s a good question.

Oh, this says actually. I wasn't necessarily wrong. It's about 16 or 17 thousand miles per hour.

Khari: Wow.

[Laughter]

Behçet: So miles versus kilometers, you know, multiply by 1.6. I wasn't wrong.

Khari: That's very fast.

Behçet: That's very fast. Good news is that the atmosphere is thinner, so that way maybe the heating is not as bad as Earth atmosphere. But the problem is then because of that you can't slow down enough.

Khari: So the algorithms that you, specifically, were working on — what were those focused around?

Behçet: Oh, the algorithm that I worked on was responsible for the fly-away phase of the mission. What happened on the Mars Science Lab (MSL) mission is the following: as I said, we enter the atmosphere, we slow down with drag forces, then we open the parachute — it's called supersonic parachute because we open it at supersonic speeds. That brings us more or less below supersonic speeds. Maybe I'm lying here? It may still be supersonic, but it slows it down even further. Then there's a point at which we cut the parachute off and we turn on the engines, the thrusters. They slow us down and as we come down this is called the "powered descent phase." "Powered" because we have the thrusters on.

We are about tens of meters above the ground when we start really slowing down. We are coming down very gently now. There's a winch on board, which has cables, and this winch lowers the rover down with the cables. The descent vehicle is hovering over the ground at that stage. When the rover touch down is detected, the algorithm that I designed takes over and stabilizes the descent vehicle during that time, because there's an offload — suddenly, you are carrying the load of the rover, which is almost the same mass as the descent vehicle, and when the rover touches the ground, suddenly, you don't have that load. It's like, you drop something, then you will have a transitional effect during that time.

Then, once that happens and when we know that the rover is safe on the ground, the cable was cut and the vehicle had to turn and burn at the same time to fly away from the rover and crash as far as possible. That was the responsibility of the controller that I designed. My job was literally to generate the first man-made crater on Mars.

[Laughter]

That's a pretty accurate description I would say. So the tricky part of the algorithm was how do you stabilize the vehicle during the contact and then turn it. When you're turning it you have to be really careful. If you turn wobbling, the thrust plume coming out of the thrusters can cause a lot of trouble for the vehicle — it can affect the sensitive sensors onboard the rover and such. So I had to really tightly control this thing and push it as I'm turning it. It's like throwing a javelin or something, you are pushing it as hard as you can. I had, literally, several seconds to push it as hard as I can, and then it's on a course to fly as far as possible, basically. And I made it fly around 650 meters from the landing location, which was great because my requirement was about 200 meters. I did it with a major margin and by using the allocated fuel.

[Laughter]

That was really successful in that way. It crashed and then they took a picture from the Mars orbiting satellite. You could see the landing site and the crash site. It was a beautiful picture, maybe I should send you after the podcast.

Khari: Yeah, if you send it to me when I announce the podcast, I'll post a photo somewhere. [View the photo here]

Behçet: Yeah, I actually saw the effect of the algorithm, which was very cool.

[Other Projects at JPL - 19:46]

Khari: Have you been involved with any other projects at JPL outside of landing on Mars?

Behçet: Oh yeah. One was, again, a flight mission, not as high profile as Mars Science Lab. It's called [SMAP](), Soil Moisture Active Passive mission, which was basically an Earth-orbiting satellite with a spinning antenna, like a flat, meter-like antenna, made up of light material. It is rotating and it's looking at the Earth's surface measuring soil moisture. I am not very insightful about the scientific objectives, I was, again, the controls engineer. My job was the [RCS system](), reaction control system, which is a bunch of these really little thrusters. You may see in the movies, any space movie, they fire small plumes, you can see the air coming out of them.

What they do is, basically, by throwing air out they inject momentum, both translational and angular momentum to control the motion of the spacecraft, both the rotational and translational motion. My job was to design the control algorithms for these reaction controls, so that we could control the vehicle's orientation and the vehicle's speed.

So that was my job. I designed those algorithms and delivered them. That's one of the missions. The other is maybe on the more technology development side. These [previous missions I was discussing] were more engineering missions, things that had to be done now. We also develop new technologies for the future. There were two areas in which I was very active. One, and maybe the most important one, is planetary landing, including the Mars landing. And also those techniques inspired some of the techniques being used right now for landing on Earth, like SpaceX landings. The people who designed those control algorithms were close collaborators of mine, we worked together at JPL and then they moved to SpaceX and I moved to academia. There I developed what can be described as optimization-based control algorithms. There is a field of mathematics called optimization or mathematical programming, it has different names. I can explain more later.

Basically, these are more sophisticated numerical algorithms to solve difficult decision problems. These decision problems may come from different fields. Basically, what I managed to do was, for landing problems I managed to formulate control problems that are relevant to planetary landing as optimization problems, which are not any optimization problems but numerically tractable optimization problems, particularly real-time tractable optimization problems. And this reformulation allowed us to utilize the existing spacecraft “more.“

What that means is [these algorithms] allowed us to fully utilize [the spacecraft’s] flight envelope. Let's say I'm landing on a planet. Because of all the uncertainties I may want to land at a certain point but I may find myself at a different point. It's pretty much guaranteed that you will not be on top of where you want to land after the entry phase of the mission. So during the powered descent phase, when you have full control with the thrusters, what you can do is divert back to the point you want to land. That turned out to be a major flight maneuver, and to be able to complete the maneuver in real-time and in a dynamically feasible manner — in a manner that the spacecraft can actually execute — you need these sophisticated algorithms. I developed maybe one of the first that was ever tested on a test rocket. That work started at JPL. I concluded that in academia later on but that started with JPL.

The other technology development project that I was heavily involved in was formation flying. This is where you send multiple spacecraft to space. Instead of sending a giant spacecraft you send a bunch of small ones. You may want to use them for scientific observations or other reasons. How do you coordinate these multiple spacecraft so that they act as one was the control problem. I also worked in that area quite a bit.

Khari: So what are the challenges to coordinating a swarm that's different from just a single vehicle?

Behçet: Of course, by having a swarm you make the hardware design easier in way. You don't have to send the big infrastructure around a large spacecraft to space, which is very hard. Payload delivery to space is one of the hardest parts of the mission. So you may be solving that problem, but you cause yourself other problems.

What is coordination? Let’s say you send four or five versus hundreds. You may send hundreds, right? Now, SpaceX is sending a bunch of spacecraft. The main challenge from a control's perspective is information passage among spacecraft. Getting the right information you need so that you can do your part in the formation, deciding on what that information is, and how do you utilize it so that you do the right thing for the mission. And while you're doing that you also have to make sure that your motion, for example, doesn't cause issues, because now you have a bunch of spacecraft and if you're not careful they may even collide. Before they were really linked so the collision wasn’t an issue, you were one piece.

But now you're going around in space at high speeds. Collisions can become detrimental to the mission if you're not careful. So there is this difficult task of coordinating them. And when I say “coordinating” I mean the following: for example, we will have a bunch of mission requirements for a system like this, and these may change from instance to instance. Every time you may have to give some decisions on board autonomously for reconfigurations. You may have to reconfigure to do one thing and then you may reconfigure again to do something else. How do you partition the duties among all these spacecraft is not a trivial problem. Of course, we can have the grounding group to make all these decisions, but in some cases we may not have the bandwidth, we may not have the time, so some of these decisions have to be made onboard. Those really make the decision problems very, very hard.

And then, of course, as I mentioned, they have their own constraints. Collision avoidance is one of them, for example. The other difficulty is that since we make this big system into a bunch of small systems...in a big system you may have really sophisticated sensors, you may have more sophisticated computing units and things like that, but when you make [the spacecraft] smaller you can’t put them on board. You have to live with maybe less sophisticated sensors, less sophisticated computational devices, less sophisticated actuators. Now, how do you do the mission with these less capable subsystems? That becomes a bit of a challenge too.

[Sensors on Spacecraft - 27:10]

Khari: So speaking of sensors, how many sensors were typically on, say, a rocket that's going to Mars?

Behçet: Oh, a bunch of them.

[Laughter]

I mean, a bunch of accelerometers everywhere to measure accelerations and such during launch and entry to Mars, because that's when it's important. During the cruising phase you may have sensors to detect stars so that you can know where your orientation is. We have a deep space network to keep track of the vehicle. Again, those are not my expertise but, you know, we have those. Those are more external sensors.

During landing we have a radar. In the next mission we will also have a camera to do what we call "terrain relative navigation." We will take pictures. This is the new big technology. By taking pictures we will know where we are relative to the ground in the horizontal plane. Typically, with radar we know our altitude but we don't know exactly where we are relative to the target in the horizontal plane on the plane of the planet's surface. So cameras provide that information to us, and since we don't have GPS on Mars we need something like that. So these are the types of sensors and depending on missions sometimes you may have specialized sensors too. They do high accuracy sensing of some quantity, depending on the mission.

Khari: So these earlier missions, they didn't use cameras for any of their positioning?

Behçet: Oh no. For MSL, for example, we didn’t use a camera. We only pretty much know the altitude, more or less.

Khari: Wow, that's crazy.

Behçet: It is, but, you know, cameras also come with a lot of caveats. Image processing onboard in real-time is non-trivial. I mean we are developing a lot of technologies but they have a lot of blindspots too. Image processing, though it has improved a lot, it's not like, “Ok, I’ll do some image processing on my laptop and make some errors once in a while and it’s fine.” You can't say that when you're sending the mission [that’s worth] a couple of billion dollars.

[Laughter]

If it gets there at the wrong time your mission is over. So these technologies, at least the parts that we use, must be really, really well verified and validated. We can’t leave things to chance, that's the challenge.

Khari: So you said you know the altitude. When the rocket is entering Mars, how is the system knowing that it's getting close and it should start deploying these different functions?

Behçet: During the mission, we keep on estimating the vehicle's position in order to land on Mars, of course. I mean, that happens constantly. So, with some errors, you know when you are about to enter Mars. Again, when we enter we really don't know from the ground, it's just after the fact. There’s some delay. But, you know, the vehicle detects it because of the...when you go from free space to an atmospheric environment suddenly the accelerations that you feel change tremendously.

Khari: Right.

Behçet: You know, suddenly you have drag forces acting on you, slowing you down. That means acceleration — or deceleration in this case — so you detect those things with your sensors and you start taking actions accordingly. And then, when we get close, there is a point at which our radar starts working. Not that we know throughout the whole landing, but we start knowing [the altitude] pretty accurately after a point. But that is also not like 100 percent accuracy, at the worst case we have 100 meters in accuracy. You may be saying, "Oh I'm 100 meters above," but you already are on the ground." That's possible.

[Laughter]

So there is some uncertainty. To handle it we had an accordion phase. We also incorporate this in our decision-making. During that phase we let the vehicle go down with a constant tolerable velocity. Tolerable means, if I establish contact at that velocity it won't kill the mission. Basically, you are going slow enough. But that means you have to carry enough fuel to allow this slow descent. If the uncertainty is large then you have to cover a larger altitude with this slow descent velocity, that means we need more fuel. So there's always this game of how do you balance the fuel needs with the uncertainty and so on.

So, we have some knowledge of what's happening. It's not perfect, and our strategies must handle these imperfections.

[Landing on Earth vs. Mars - 31:42]

Khari: Yeah. Circling back to something you said earlier — you were talking about SpaceX working on landing rockets on Earth. I watched a couple of YouTube videos when I was preparing for this where I saw them trying to do the vertical landing of the rockets. So, do you know, what are the challenges to landing a rocket on Earth compared to on Mars?

Behçet: Oh, yeah. I mean, the Earth’s atmosphere is much thicker and you're coming with high speeds when you come from orbital speeds. The hope is that we will also have vehicles returning from Mars, which will have even higher speeds. Now you have to enter the Earth’s atmosphere where you're heating up more. There is this “heating load” they call it.

You have to come down such that you don't burn the vehicle, you don't cause damage and such. Then you are interacting with a thicker atmosphere, so it's affecting your motion tremendously, and you are trying to aim for a bullseye on the ground.

[Laughter]

Or on this water in this case. They have these ships that they land on.

Of course, the advantage is you have GPS, for example. You know your location better and so on, but now you are dealing with a dynamically harder environment with a thicker atmosphere. That's the main problem — that has been the problem, and that's going to be a problem in the future, too. As they increase the payload capacity of these vehicles, they make them larger and such, landing on precise targets will always be a challenge.

Think about it: you are trying to land on something that's moving, ultimately. Both in terms of rotations because of the waves, and also, you know, because of the currents. So as you're coming down, you have to stick the landing. This is not an easy thing, both from an algorithmic point of view as well as the hardware design. How do you design hardware so that you can take the impact forces that can occur during landing? Those are very, very challenging problems.

SpaceX has been very successful. But of course, they have their failures also. Increasing consistency, you know, making it almost like taking a flight, that level of accuracy requires more and more development.

[Working at JPL and Career Advice - 33:55]

Khari: Right. So, I mean, overall, what was it like to work at JPL? What was your favorite part of working there? Or least favorite part?

Behçet: I must say, my favorite part is working with people who knew what they were doing. There were a lot of world-class, top notch experts. They're sometimes the only expert in a certain area almost. By expert I mean, not only having the knowledge, but they have exercised that knowledge. They have a major amount of experience. Deep knowledge plus experience makes you an expert. And there were people who had these qualities at JPL, technical people, and I loved working with them. I learned a tremendous amount of, not only knowledge, as I said, but I learned a lot about their experiences. That was really, really amazing.

The second piece is I also gained my own experience. I contributed to missions, I contributed to new technologies. By contributing to missions I learned how to handle a real-world system, how to think about it, and how to parse the problem so that when you solve each little problem and put them back together it solves the actual problem. I worked on technology development, then I learned it's not all about solving a math problem, it's about how to promote this technology. All these pieces, from very technical development to somehow promoting the technology, which sounds like marketing almost and it is maybe. Learning about all these things was really eye-opening. I mean, both technically and in terms of human interactions, I think they were the most fulfilling experiences. It was almost like a completely new education for me as an engineer and as a researcher.

Again, the most favorite part is dealing with the experts, top notch experts, but the least favorite part, also comes with dealing with people. Dealing with people is sometimes a good experience and sometimes bad. It's an organization ultimately. There is a hierarchy and within the hierarchy everybody has to protect certain things. If they don't do that the institution may be hurt. That's why there are many rules in this environment.

You live in that hierarchy, and sometimes that hierarchy restricts you, and when it restricts you it's upsetting. But it also enables you, right? That's when you are happy. So when it enables you you are happy, when it restricts you are unhappy. I think you go back and forth between those two. But overall I think JPL made me the engineer I am, so I am really grateful that I had the opportunity to work there.

Khari: So for listeners who might be interested in working at JPL or NASA or SpaceX or similar kinds of things, do you have any advice about things to expect or, you know, topics you think are more important to study? Things you were surprised by when you started working there?

Behçet: Let me start with the technical parts of things. I think if you want to be an engineer working in controls, let’s say, I think it's important to have strong key, basic skills — the fundamental skills. It’s like in everything you know, you have to have strong fundamental skills. You can't just imitate the outcome of those skills. It's true for everything.

Like, I used to do sports — when I was way younger of course, now I am doing it just to keep healthy — and I used to see people doing amazing things. If you want to just imitate what they do you will always fail because those skills come with years of working on fundamentals. Sometimes those fundamentals may not even look relevant to what's going on with the output. But you have to work on your fundamentals. And that's true for engineering and science, too. If you don't have strong fundamentals...these fancy moves or results don't come out of something superficial. So I think working on your fundamentals is the key.

Rather than being a cool rocket scientist, you should think about being a person who can solve problems. Rather than striving for being somebody, striving for being able to do things I think makes you a better engineer in my opinion. Then you will gain your own character and you will be somebody anyways.

Aso when you work in a big organization a part of the job is, again, working with people, which, unfortunately, we learn on the job most of the time. I mean, even technical things you learn on the job but you get a lot of training, you get a lot of skills during your education that prepares you for that. But typically, when you do grad school, like Master's and Ph.D. you are kind of by yourself most of the time. [You are with] your advisors, maybe a couple of other students. You are with a limited group of people in a limited context. But when you are in a big organization you work with a bunch of different people in different contexts.

I wish I had learned more about how to work with people with different objectives, with different technical and social backgrounds, because that's where you really get into trouble, right? Because you're not trained for it, you are learning it on the job. You may not have the right sensitivities. I think that's where our education system is maybe not preparing us as well. We gain experience by interacting with other fellow students and professors, but those are different experiences. I wish there was a bit more formal education on how to work with people. That's the part that I thought that I could have benefited tremendously. How do you do career planning? Like, I didn't even think about those things. I went there and I want to just do things.

But, again, there are other things you have to be cautious about so that you have a much smoother career and work-life balance and all these things. Maybe if you are conscious of these things in advance you may prepare yourself better. Maybe that's advice I would have given to someone else who is coming up. I wish somebody gave me that advice before.

Khari: Yeah, I think that's good advice. I think a lot of...at least in the U.S. school system there's not that much teamwork, so then working in a team is a skill people have to learn.

Behçet: I agree. I mean, that's true everywhere because part of the education system is, I guess, measuring you. Always they try to measure you. Are you a good student, that’s always the question, right? In primary school your uncle sees you [and asks], “Are your grades good?”

They never ask you, “Do you get along with your friends and do things together?”

Maybe they ask you, but that's not the primary focus of the question. One of the goals of the education system is measuring people and maybe that makes it a bit of an individualistic thinking [environment], which is fine, but I think this collective effort is hugely important. That's how we accomplish things ultimately, and being prepared for that type of effort, I think it makes a difference. I wasn't well-prepared. I had to learn it on the job.

[Outro - 40:56]

Khari: That's it for this episode of the podcast. We'll be back next week for part two of my interview with Behçet. In that episode, Dr. Açikmeşe discusses control theory and the work of the University of Washington Autonomous Control Lab. Until then remember to like, subscribe, and rate us five stars wherever you get your podcast. Until next time, peace.