Dr. Shelton:

Haley earned her bachelor's and master's of science degree in mechanical engineering right here at Northern Illinois University. Go Huskies. After two internships at NASA Ames Research Center's Rotorcraft Aeromechanics Branch, Haley was hired as a Pathways Intern while completing her master's degree and converted to a full-time employee upon graduation. Haley's task at the Rotorcraft Aeromechanics Branch has included design, analysis, and manufacture of a wind tunnel test stand for testing urban air mobility vehicle concepts.

Recently, Haley and her team won a proposal for which Haley is the principal investigator entitled, Rotorcraft Optimization for the Advancement of Mars eXploration, ROAMX, which seeks to improve the scientific capabilities of Mars rotorcraft to enhance Mars exploration. Haley is excited about using rotorcraft to explore both terrestrial and extraterrestrial terrain, and she'll be talking to us today about the Ingenuity, the Mars helicopter. So, once again, we'll give our undivided attention to Haley for about 20 to 25 minutes, and then we'll allow for some questions afterward.

Haley:

Awesome. Again, thank you very much for the introduction. I'm really excited to be here today talking with y'all. As Dr. Shelton said, my name's Haley Cummings, and I work at NASA Ames Research Center. I appreciate the introduction, but I, of course, have to give another shout out, go Huskies. I did play soccer ball at NIU, and I also did some research in my master's program with Dr. Vahabzadeh. A huge shout out to NIU. I'm excited to be here talking with y'all today. As Dr. Shelton said, I had two internships at the Rotorcraft Aeromechanics Branch with at NASA Ames, and those were really instrumental internships, make a big difference. So those are awesome. I did get hired as a Pathways Intern, and after I completed my degree, got hired full-time at NASA Ames.

I want to talk about Ingenuity today, but first I want to talk a little bit about why are we even interested in flying on Mars? There's several reasons. The main way that Mars is explored today is by rovers and landers and satellites. Now, rovers can do a lot of science. They have a lot of equipment on board, but they're limited in the types of terrain that they can access because they need to stay on pretty much flat terrain. They don't do well navigating around obstacles, and it takes a long time for rovers to travel.

On the other hand, satellites have relatively low resolution. They do a great job of mapping planets, specifically, I'm talking about Mars today, but they have relatively low resolution. So rotorcraft or flying on Mars, in general, but, specifically, I'm really excited about rotorcraft, they can bridge the gap between those two.

So in the graph that I'm showing over here on the right side of the screen, you can see the path that the Curiosity rover traveled in five years, and that's outlined in yellow. It took Curiosity about five years to travel that path, whereas an advanced rotorcraft that's using advanced rotors, which we'll talk about later, that rotorcraft could travel that entire distance that the rover traveled in five years and only three days. So rotorcraft are not limited to the requirement of a nice terrain. They can fly next to cliffs and over trenches. They have a lot more versatility in where they can explore. They also can take more detailed imaging of Mars compared to satellites. They can kind of bridge the gap between the zoomed-out view that satellites bring and the kind of zoomed-in view that rovers bring.

In terms of why, again, why it's important to even do science on Mars or what we can accomplish when we fly on Mars, some of the science that would be enabled in this table on the left, you can see that we would be able to do more mapping of Mars. We could do science in the polar regions. We could do atmospheric science. We could even do subsurface geophysics. These are just a few examples of the types of science that a rotorcraft could do. Over here on the right, just giving you a broad, general overview of the types of things that a rotorcraft could do. We have a couple of instruments that a rotorcraft could carry. So a rotorcraft can do significant science on Mars, and that's really exciting.

The next kind of natural question becomes why is it hard to fly on Mars? There are several reasons... There's several challenges, and I've got them listed here. Autonomous navigation is a big one because there's a huge communications delay between Mars and Earth, so if you want a helicopter to be able to fly, it needs to be autonomous. We can't be sending directions to the helicopter because by the time the directions got to the helicopter, it would've been long gone, the time whenever it needed to know those things. The helicopter has to be able to fly autonomously.

The flight dynamics and control is just different on Mars than it is on Earth. There's a lot less air, which I'm going to talk about a lot more in just a second, and that makes it really difficult to control the helicopter. The dynamics and control that's required is different than that on Earth, and we don't fully understand it. It's difficult to test. One of the reasons it's difficult to test is because there's also a weight reduction. Mars has, I think, about a third of the gravity that Earth has. I think that's right, and so if you're trying to replicate the conditions that you're going to find on Mars, it's difficult because there's less gravity on Mars.

Then the one that I'm most interested in is the aerodynamic performance. The aerodynamic performance on Mars is affected by two main parameters, and those parameters are the density of the air and the temperature. You can see here that the density of the air on Mars is a hundred times less than that on Earth, and the way that helicopters or airplanes fly is by... Well, helicopters fly by spinning the rotors. You have a difference in pressure over the rotors and that creates lift, but that's created by the air particles that exist. On Mars, there's a hundred times less of those to fly with, so that's a really difficult challenge to overcome.

The temperature is also way less than on Earth. You can see here 15 degrees Celsius is an average on Earth. It's a little colder for y'all in Illinois right now, but on Mars, the temperature's negative 50 degrees Celsius. That's an average. That's what Ingenuity was designed to fly in, but it's a lot colder on Mars. What these parameters translate into is the density being a hundred times less translates into a much lower Reynolds number.

The Reynolds number is a parameter that we use in aerodynamics. If you haven't learned about it yet, I'm sure you'll learn about it in your fluids class when you take that. But the Reynolds number, excuse me, is basically the ratio of inertial forces to viscus forces. It's a key parameter in aerodynamics and understanding how the aerodynamics behave.

On Earth, a typical airplane, typical helicopter will fly at about 1.3 million Reynolds number, where on Mars, the average along Ingenuity's blade is only 19,000. We'll talk about that a bit later in more detail, but it changes the aerodynamics and makes it difficult to fly. In addition, the temperature being so much less impacts the speed of sound. To hear the speed of sound on Earth is 340 m/s, whereas on Mars, it's only 233 m/s.

So when the blades are spinning, you get a Mach number, and usually on Earth, we're relatively low subsonic Mach numbers, but on Mars, for those same RPM, the same revolutions per minute that the helicopter is spinning with, you have a much higher Mach number. As you get closer to spinning at Mach 1 or at the speed of sound, you start to develop shock waves over the blade, and those can start as early as 0.8 or 0.85 Mach number for some of the newer optimized blades that we've been looking at. That's also a concern, the shock waves, they cause the drag to seriously increase, and that makes it difficult to fly on Mars. So those are some of the challenges, but the bottom line is we did it anyway.

Ingenuity was an incredible design process. We'll talk about it a little more in a second, and there's so much more that can be improved upon. That's one of the really exciting things about engineering is there's always work that can be done.

So taking you back in time a little bit, since the late 1990s, and even before that, researchers have known, have seriously believed that rotorcraft could fly on Mars. This picture on the left here shows a test that one of my colleagues conducted back in the late 1990s at Ames in a vacuum chamber, where they were trying to understand more about the aerodynamics on Mars and what it means to fly with little to no air density. So they put this rotor in a vacuum chamber, they evacuated all of the air, and they spun it up to try and understand what it means to fly with little to no air.

These concept vehicles on the bottom of this screen are some university concept vehicles that were generated around the same time. Several of them were generated for a vertical flight society competition, so flight on Mars is nothing new. But one thing that I learned from my relatively short time in NASA is that if you want to bring an idea to life, you have to have two things. You have to be able to paint a picture, and tell a story about why what you're doing is interesting, and why it should be done.

You also have to be able to seize the moment and take advantage of opportunities whenever they present themselves. So here on the left, I'm showing Dr. Bob Balaram, who, around 2015, with his team, wrote a proposal to fly a helicopter on Mars and to include it with the Rover on the Mars 2020 mission. They won the proposal, and they began the design process. What resulted was the Ingenuity Mars helicopter.

When Ingenuity flies on Mars, it will execute the first ever powered extraterrestrial flight, and that's huge. I mean, I'm really excited about it. It's landing with the Mars Rover on February 18th of this year, so it's coming up really soon. It's basically a technology demonstrator. So there's five flights that are planned, and these flights are planned to be about 90 seconds each, and Ingenuity is only going to travel about 180 meters max. It's relatively limited, but as a technology demonstrator, it's going to revolutionize the way that Mars is explored.

This is just a graphic that shows Ingenuity next to the Mars Rover. The Mars Rover is about the size of a small SUV, a small car, and Ingenuity is just a little guy. It's 1.8 kg., and the blade diameter is 1.2 meters. So it's pretty small, but, like I said, it's going to revolutionize the way that we explore Mars.

This here, sorry for the poor quality picture, but I don't know if you can see my mouse, but Ingenuity is pictured here in this box in the upper right corner. If you look here, the Rover is flipped upside down in this picture, and you can see Ingenuity's blades right here. It's stowed in the belly pan of the Perseverance rover. So whenever the Perseverance rover gets to Mars, it's going to drop Ingenuity off onto Mars. It's going to drive away, and then Ingenuity is going to unfold and take off from there and perform it's five flights over 30 days.

Some of the work that was done in my branch, at Ames for Ingenuity was some of the comprehensive analysis and computational modeling. As I mentioned before, we don't fully understand the aerodynamic performance or how things happen on Mars. So one of the goals here in this graph that you can see on the left is to perform a comprehensive analysis and compare it to the experimental results that JPL got for their experiment that they did with Ingenuity. So one of my colleagues, Witold Koning, generated this graph, and you can see that we have figure of merit on the Y axis and the thrust coefficient on the X axis.

For helicopters, figure of merit is a measure of the performance of the blades, and, basically, it compares the ideal power that the blades require versus the actual power that's required. You can see here that with the comprehensive modeling that was done, we have a pretty good correlation between the experimental results and the computational modeling. Then on the right side here, we have computational fluid dynamic simulation of the outboard portion of Ingenuity's blade, of the airfoil cross section of the blade. That was some of the computational work that was done at Ames.

We also did some experimental testing. In the same vacuum chamber that was used in the early 1990s, we took a surrogate Mars helicopter blade, so a surrogate Ingenuity blade, and we put it in that vacuum chamber. You can see on the top right picture, that is the blade in the wind tunnel in forward flight, and the bottom right picture shows the wind tunnel that we used. We were doing this, again, to try and understand better the aerodynamic performance of blades whenever they're under reduced air pressure. The results from this showed, as we expected, as you decrease in air density and as you decrease in Reynolds number, you get a decrease in performance. I'll talk about that a little bit more in a second, but I just wanted to give you a complete information overload and just say that, at my branch, we've really been inspired and super excited by Ingenuity as I hope you are.

In the past, I want to draw your attention to this image, the second image from the left... We did go down to JPL and conduct a hover test in their space simulator. Then if you look to the right... As I said, we've been inspired and excited by Ingenuity and the possibilities if a detailed design process could really be pursued for a Mars helicopter, and result of that has been the Mars science helicopter, which my colleague, Shannah Withrow is going to talk more about in a few weeks.

But I wanted to talk a little bit more about the aerodynamics of flying on Mars and what we're doing to better understand the aerodynamics and also improve the performance of future Mars helicopters. As Dr. Shelton mentioned at the beginning, my team and I recently were awarded a proposal to... The title is Rotorcraft Optimization for the Advancement of Mars eXploration. We call it ROAMX. In this proposal, our goal is to computationally optimize blades for flight on Mars and to better understand the aerodynamics, especially for that low Reynolds number and relatively high subsonic Mach number regime that we encounter on Mars.

Then once we've done a computational optimization, we're going to move into experimental validation to spin up the blades that we design so that we can say, yes, our computational modeling was accurate, and we can use these blades for future Mars rotorcraft. Oh, I had to export this as PDF at the vein, so my graph is not going to turn out like I was hoping. My apologies, but, basically, Ingenuity, as a technology demonstrator, is a fantastic piece of research and dedication and technology, but it is pretty limited.

It doesn't carry any science payload, and it has a relatively low hover time and low range. With the optimized blades that we're looking at for ROAMX, we are proposing that instead of flying 180 meters, we could fly 6,000 meters, and we could also carry 1300 grams of payload. As we looked at, if you remember, all the way back to the beginning, that translates into a significant amount of scientific equipment that could really be used to explore Mars in a totally new way, in a revolutionary way. That's why we're doing ROAMX, and it's just one piece of the puzzle. There's a lot of other vehicle design that has to go into it, but the aerodynamics and the blade performance really open up an entire new regime that we can use to explore Mars.

So I say computational optimization, and whenever I say that, I'm referring specifically to the airfoils or the blade cross sections. On the right here, going from the bottom to the top, you can see that we're showing some relatively conventional airfoils for relatively low Reynolds number, at least as it is on Earth. Then we're showing that the airfoil that we've used for Ingenuity, but this airfoil wasn't specifically optimized for flight on Mars. It works, and Ingenuity's going to fly, but we think that some additional work, we can optimize airfoils that will be much better.

You can see on the top, there is one of the preliminary airfoils that we've optimized for ROAMX. It's specifically characterized by a sharp leading edge, which we call this the leading edge here at the front. That's the part that goes into the wind and a relatively thin across the corridor or this relatively thin across here. It's thin because by keeping it thin, we can mitigate the compressibility effects or what happens whenever we spin at a relatively high subsonic Mach number. So that's why we're keeping it thin.

It's fascinating to me because if you look here on the left, you can see that nature had it figured out from the very beginning. Nature knew that for lower Reynolds numbers, you can't use conventional airfoil shapes. If you look there at the top, you can see that's the cross section of a dragonfly wing, and it doesn't look anything like what we use to fly here on Earth, but it's around the same Reynolds number as we experience on Mars. So with these kinks and sharp edges, a dragonfly is obviously able to fly really well. That was kind of our inspiration for looking into these unconventional airfoil shapes as we call them.

Going further on that, what we're doing is a computational rotor optimization, where we are optimizing airfoils for use in the low Reynolds number, relatively high subsonic Mach number regime that is found on Mars. Once we get the airfoil optimized, we're going to move to optimizing the blade planform or the overall shape of the blade, specifically, again, for use on Mars. Once we do that, we are going to put the rotor back in that same vacuum chamber that we've used previously, and we're going to spin it in hover to compare the results that we get, the performance results that we get in our experiment to our expected computational optimization results that we get via computational fluid dynamics and comprehensive analysis.

That's just the first part of the story. As I mentioned, there's a lot more aspects that go into this as far as vehicle design and dynamics and controls. I'm not going to talk about them today, but my colleague, Shannon Withrow-Maser is going to go into more details about the vehicle design for future Mars helicopters because, again, we really believe that Ingenuity is going to set a precedent. I mean, at least I hope so, but that the future of Mar exploration is with rotorcraft.

I know there was a lot of information. If you want more information, my branch website is a fantastic resource. You can look for authors, Shannah Withrow-Maser, Witold Koning, Natalia Perez Perez, Larry Young, Wayne Johnson, Geoffrey Ament. They all have papers that they've written about the work that we've done specifically for Mars rotorcraft on that website. I have to give a huge shout out to Shannah because she helped me out with these slides and Natalia, basically, this is her slide deck, her inspiration. That's all the content I have for today, but I'd love to take questions.

Dr. Shelton:

Well, first of all, we want to say, thank you, thank you, thank you, Haley, for this excellent presentation. I think I speak for some of the faculty that are here and staff. We're really proud of you. You represented us well today, and you represent us well at NASA. Thank you very much. You did an excellent job. Once again, we're going to open the floor to questions from the audience. There is going to be a poll that's going to go up. I'm going to ask the first question, and then if there's another set of questions on from another co-host that they would like to bring up, then that's fine. We can alternate, go ping pong back and forth.

So, Haley, my first question for you is this. Now because you're dealing with relatively high Mach numbers and high compressibility, is there going to be a partial-slip boundary condition at the wing surface, and is there going to be some thermal stresses applied to the wing as a result of the high compressibility that's going on at the wing?

Haley:

That's a great question, and, disclaimer, my expertise is not so much in the aerodynamic side, but I'm going to give that a shot. One thing my colleagues, specifically Witold Koning, he's been looking at trying to understand the flow that goes on at these low Reynolds conditions. He's recently, and he hasn't published it yet, but it's going to be coming out soon, but he's recently done an entire study comparing the Eppler 387 airfoil that Langley did a bunch of experimental testing on. He actually did recently, like I said, just finished it, a computational fluid dynamic study on. He's finding that the conventional wisdom really doesn't apply at the low Reynolds numbers. So the way that Laminar Separation Bubbles are propagated in the literature is it's different at the really low Reynolds numbers. So be on the lookout for that paper. He explains it much better than I do, and some of his other papers, he goes into a lot more detail. Like I said, sorry, I don't have the full knowledge there.

Dr. Shelton:

Oh, no.

Haley:

But as far as the stresses, that's something that we've been very cognizant of because the design of a blade is, inherently, it's a systems engineering process. We're looking at aerodynamics, but you can't ignore the structural side of things. So it's been challenging because we don't have any specific requirements as far as the structural side of things go, but definitely as you make those blades thinner and thinner, you're going to have flapping and resonances that are going to creep in. So we need to keep the blade as thick as we can while mitigating the compressibility effects. So we've been talking with one of our partners, AeroVironment, we've been talking with them about how do we make sure that we're paying attention to the structural requirements while also optimizing the air dynamics as much as possible.

Dr. Shelton:

Okay. Thank you, Haley. Thanks for a lot. That helps a lot. Are there any other questions from other co-hosts?

Speaker 3:

Yes. I had another question. I'm sorry, I can't pronounce the person's name correctly, but what materials are the blades of Ingenuity made of?

Haley:

Yeah, that's a great question, too. So they are carbon fiber with a... I believe they have a spar through the middle, but they're carbon fiber.

Dr. Shelton:

Cool. So any other co-host have questions that they'd like to share?

Speaker 3:

We did have another question about if the recordings will be posted somewhere, so I thought, Dr. Shelton, you might want to explain what's going to happen with these.

Dr. Shelton:

Okay. Well, that's an excellent lead in, but before I do, I want to go ahead and say one more thank you to Haley for giving us her presentation today. That was excellent, and we really do appreciate this.

Okay, then, so what we're going to do is this. Our videos are being recorded, and they're going to be posted, but they're being posted on our Massively Open Online Course system that we are currently developing with the University of Illinois, Northern Illinois, and our MOOC Development Corporation, our MOOC Development Educational System from [inaudible 00:29:16] Education.

Once we start getting everything together, we're going to let everyone know where these videos are going to be hosted. They are part of an actual educational platform, so you'll be watching the videos as well as being asked questions about what you learned, what you didn't learn. Really, it's almost like a little short course. It's about two or three.... We're going to break up the videos maybe or have one video there. Then you'll answer questions about it, and there'll be some handbook information for you to learn a little bit more about it.

But once we get the website together, we will let everyone know that has... because we have everybody's contact information. So everyone that attended today will get the email, so that they can watch the video when it's posted. We still have to edit it and upload it, so it's not going to be anytime soon. But once we do, we'll let everyone know that the videos are there, and you can watch them there.

With that being said, we want to thank everyone who attended today. We do have another exciting set of presentations for next week. First of all, we'll be having Dr. Joshua Roby from the University of Illinois, and he'll be giving a talk about space propulsion. Then we have a second one. His name is Dr. Shelton. He'll be talking about thermal energy storage and space applications. You're more than welcome to come, sign up, just like you did for this one and get ready with a lot of questions. Hopefully, we'll have a good time next week as well. Thanks everyone for attending, and we'll see everyone next time.