Danielle (00:14):

I would like to now introduce Dr. Joshua Rovey. Dr. Rovey received his bachelor's, master's and PhD degrees from the University of Michigan. Prior to joining the University of Illinois, he was professor at the Missouri University of Science and Technology where he founded and directed the Aerospace Plasma Laboratory. In addition to being an associate professor of aerospace engineering at the University of Illinois at Urbana-Champaign, Dr. Rovey is also the director of the electric space propulsion laboratory and director of the Illinois space grant consortium. In 2016, Rovey received the AIAA Lawrence B Sperry National Young Professional Award. Rovey's research focuses on the space propulsion with a specific interest in electro spray, material interactions, contamination due to the ground based facility interactions, and multimode propulsion approaches. Today, we will hear a little more about his research since topic is on electric and chemical propulsion.

Dr. Rovey (01:29):

Great. Thank you very much, Danielle. Appreciate it. Yes, so today my topic is going to be on propulsion, propulsion for spacecraft, space vehicles. And in particular, I'll talk about, we call multimode propulsion. I'll talk about what that is, exactly what the benefits of multimode propulsion are. And then I'll talk about a specific type of multimode micropropulsion that my lab has been working on. I want to acknowledge graduate students who've worked on this topic over the years, as well as our sponsors for this research.

So I'm talking about space propulsion and there's two main types of space propulsion, chemical propulsion and electric propulsion. And in chemical propulsion systems like the space shuttle, you see here in the top right hand corner, chemical propulsion systems rely on the chemical energy stored in the bonds of the propellant to provide energy to the spacecraft or to the rocket, to the vehicle.

These are photographs of a couple of reaction control rocket engines. These are attached to the sides of the spacecraft to provide attitude control, pitch roll, they all of the spacecraft, but they all operate off the same principles. They take an energetic propellant, a chemically reactive propellant, and they decompose it in a chemical combustion reaction, which gives rise to a high temperature gas that's exhausted out of a nozzle generating the transfer momentum that provides a force on the vehicle and generates what we call thrust.

Chemical propulsion's generally very high thrust propulsion systems generating anywhere from newton's to kilo newton's of thrust for spacecraft, but they're generally low. What we call specific impulse and specific impulse is a measure of how effectively the rocket uses its propellant. The mass that it's expelling out, how effectively it uses that propellant to provide energy delta. What we call delta-v to the spacecraft, how effectively it applies an impulse and accelerates the spacecraft. So chemical propulsion is generally very high thrust, lots of acceleration, lots of force, but generally it doesn't use the propellant very effectively to impart impulse to the spacecraft. That's to be contrasted with electric propulsion.

Electric propulsion uses the onboard electrical power of the spacecraft. So not chemical reactions, not chemical bond energy. The energy for propulsion now comes from the onboard electrical power supply. So the spacecraft is getting energy from solar panels, storing that in batteries, and then using that energy from the batteries to power the propulsion system. You see two photographs of electric propulsion systems down at the bottom here. This is a whole thruster. This bluish glow is the plasma, the ionized gas that's being accelerated and expelled out of this whole thruster at 10,000 meters per second or more. Over on the right hand side, this is a gritted, IM thruster. And again, the bluish glow inside here is the plasma gas, the ionized particles that are getting expelled out.

So many electric propulsion systems can also be thought of as ion engines or ion thrusters or plasma rockets. They generally have very low thrusts. So now we're talking about milo newtons of thrust, or maybe even less, but they have very high, specific impulse. So they use the propellant. They use that expelled mass very effectively to provide impulse, to provide energy to the spacecraft. They're best for station keeping very low, low thrust maneuvers.

So next multimode propulsion. What we want to focus on in multimode propulsion is really getting the best of both worlds and that's combining chemical and the electric propulsion into the same system and getting the best of both worlds. So that way, if you have a high thrust, a very fast, quick, high thrust, high acceleration maneuver, you can use the onboard chemical propulsion to do that. If instead you need to do a slow, low thrust, but very high, specific impulse, really good utilization of the propellant, you've also got electric propulsion onboard the spacecraft to do that in a multimode space propulsion system.

Now this is to be contrasted a little bit with what's called hybrid propulsion. So this is already done to a certain extent in what's called hybrid propulsion. But hybrid propulsion, they're completely separate systems, the chemical propulsion system is completely independent from the electric propulsion system. With multimode propulsion the key attribute is shared propellant. The propellant that's being used to propel the vehicle is the same for both the chemical and the electric propulsion system.

For instance, this is a system I'll talk about in a little more detail in just a second. So here you have one propellant tank and it has a common chemical propellant called hydrazine in it, but it can be fed into a chemical rocket and get really high thrust for a fast maneuver. But you see the specific impulse is only 250 seconds relatively low. So it doesn't use that propellant very efficiently. That same propellant can be used to embed into an electric rocket, this arc resistive jet. It's going to be lower thrust. So it's going to take you longer time to complete the maneuver, but it's much more efficient, 300 to 600 seconds specific impulse. It's going to use that propellant more efficiently to do that maneuver for the spacecraft.

I also want to contrast or kind of show the difference between this system right here, which is multimode and it's combining chemical and electric propulsion together, but they are separate thrusters. It's one propellant tank, but it's feeding a chemical thruster, or it can also feed an electric thruster. And they're separate thrusters. What we're working on in my lab right now is what's shown on the right hand side here. This is a multimode propulsion system.

It's one propellant in one propellant tank, but notice it's feeding one thruster. So now there's just one thruster and that thruster can be switched between operating in a high thrust, high force, low specific impulse chemical mode, or it can be switched over to the low thrust, but high specific impulse electric propulsion mode. And combining these together can help reduce mass, reduce volume of the system. And that's incredibly important when we talk about small satellites, these cube satellites, small satellites, hundred kilogram class spacecraft and smaller.

So the benefit, why would you want to do multimode propulsion? What's the benefit of having this single propellant, this single propellant tank, but being able to feed that propellant into either your chemical mode and do high thrust, or your electric mode and do low thrust. The benefit is flexibility and adaptability of the spacecraft. You have the ability to change the spacecraft mission parameters on the fly, even post launch, potentially. And it also gives rise to what we can call assembly line spacecraft, a whole bunch of identical space, like hundreds of identical spacecraft that can be launched and all execute drastically different missions.

So let me talk about what's shown here in this plot, this plot right here. So on the X axis is the propulsion system thrust. And so of course we have a high thrust chemical mode and we have a low thrust electric mode. And then on the Y axis here, this is the spacecraft delta V. This is how that thrust of the propulsion system provides energy, the energy, the impulse that's being provided to the spacecraft.

So if we took a spacecraft like the one described up here, a hundred kilogram spacecraft, and we only have chemical propulsion on board, just the high thrust mode, that spacecraft is confined to this blue line over here. And so as the chemical thruster uses propellant, it's giving energy delta-v to the spacecraft. We're moving up this blue line until eventually we run out of propellant, used all the propellant up. We've arrived at the tip of that blue line. If instead, a spacecraft had only electric propulsion on board, now we're on this low thrust red line over here. And again, as we move up the red line, the electric propulsion system is using propellant, providing energy delta-v to the spacecraft. Eventually we arrive at the tip, the top of this red line.

The benefit of having multimode propulsion is that you can do those blue and red, chemical and electric maneuvers and you can do everything in between there as well. You can do everything on this black line. And in fact, then you can think about, I could launch four identical spacecraft, four identical spacecraft, and they can do drastically different missions. The first spacecraft can do mission one, which is described over here, a rapid 12 hour 180 degree orbital phase change, and then returning to its original orbit. The second spacecraft could do this mission number two. The third spacecraft could do mission three. The fourth one could do mission four.

And so now we can think about an assembly line of identical spacecraft, maybe a hundred spacecraft getting launched on the same launch vehicle and all of them doing drastically different missions in space. This can bring down the cost and is really a paradigm shift in how we think about designing and launching and implementing spacecraft. Today, we spec out exactly what we want the spacecraft to do when it gets in space and we design it, we design it as a one off spacecraft. We design one spacecraft to do exactly what we want it to do in space.

But now we could start thinking about a common spacecraft configuration coming off an assembly line. And now that spacecraft could be used to do a very quick, timely, high thrust maneuver using only chemical propulsion or an identical spacecraft could be launched. And it could do a slow, low thrust electric propulsion maneuver, drastically different missions, but the same spacecraft architecture for all of it. Let me transition now, hopefully convincing you or explaining to you what multimode propulsion is, why you should be interested in it, why it's beneficial, what the potential benefits are.

And now let's talk about the specific type of multimode propulsion that's going on in my lab right now. One of the main projects we've got going on. Again, we're combining together chemical and electric propulsion. And here we're combining what's called microtube, a microtube chemical propulsion system with an electric electrospray propulsion system. Now at its fundamental level, at the fundamental level, this propulsion system is really just a tube, a small diameter tube, maybe a tube or a cap area, microtube with a diameter of on the order of a hundred microns or 10 microns on that order.

So if you look at this schematic, the way this works is if you were to heat that tube. So we're using this power supply to heat the tube. We feed the propellant in to that heated tube. And when this propellant, when it comes in contact with that heated propellant tube, it decomposes, it starts to exothermically decompose, giving off energy, giving off heat, and you get a high temperature exhaust gas coming out the exit of this tube.

Now, if instead, same geometry, same setup, same tube. Now we use that power to create an electric field between the tube and this downstream extractor electro. This is just a piece of metal with a hole in it. We feed the propellant into this tube, but now that propellant, the liquid propellant feels a strong electric field at the tip of that tube. And that electric field will cause individual molecules, individual molecules, or small droplets of the liquid to get extracted and pulled out of the liquid.

And so now you have a spray, a spray of these molecules and droplets being emitted out of the same tube. And so you can think about switching between these two modes, where you're heating the tube and causing a chemical reaction, releasing that chemical bond energy, getting a high temperature, high exhaust velocity gas coming out, or you apply the energy as an electric field.

And now you electrostatically extract and accelerate these individual molecules and droplets out of the liquid. And so you can switch between these different modes. Now, one of these tubes by itself is not a thruster because the thrust levels, the force from one tube is just way too low. So a thruster would actually have an array, a multiplexed array of these tubes. And I'm going to show one of those here coming up. It would look something like this, where you can see each of these is an emission site where gas in the chemical mode or ions and droplets in the electric mode would be sprayed out.

A major challenge to this is the propellant, the liquid propellant. Creating or having a liquid propellant that can be both chemically reactive and exothermically decompose, and also respond to that electric field in the electrospray mode. Most conventional propellants we use today, can't do that. They're either designed to work just as chemical propellant or they're designed to work as just electrospray propellants. They can't do both. And so that's been a major research activity in my lab is doing propellant design work.

And what we've done, is we've created our own custom, a novel new propellant. This is a new rocket propellant that we've designed, developed and we synthesize in the basement of the aerospace engineering building on the U of I campus. It's a mixture of two liquids. One, the first is the fuel and it's this emim ethyl salt. It's an ionic liquid. And the oxidizer that we mix with it is called HAN, hydroxyl ammonium nitrate. Together, both of these form an ionic liquid. Ionic liquids they're salts that are liquid at room temperature.

So like table salt, sodium chloride, that's an ionic substance, but it's a solid at room temperature. But if you were to heat it up, table salt would melt into a liquid phase. And then you would have an ionic liquid. Well, these liquids are ionic liquids at room temperatures. A major challenge when you create a new chemically reactive propellant, like we've done is the linear burn rate. When you ignite it, how quickly does it burn? What's the speed at which it burns? That's what we call the linear burn rate.

And the linear burn rate is important because we're trying to combust or decompose this liquid in a small capillary tube, in the small tube. Now you're feeding the liquid in from one direction. And then the burning front, where you have this decomposition, the liquid is decomposing into a gas. That process wants to propagate upstream into the liquid. So you have to balance those two effects. You have to feed the propellant in at a rate that balances and matches the burning rate, the propellant wants to move at going in the upstream direction.

And so we've done a series of studies, and you're seeing in this video over here on the left, these linear burn rate experiments, we've done where we start with a vial of our propellant. So you've got a tube with liquid sitting in it. We light it, we ignite it at the top. And then we watch as the propellant, the liquid is consumed and the liquid is converted to gas as that burning front moves down through that liquid, converting the liquid into a gas phase. So you can see it propagating downwards here down through the tube. And we measure that burning rate as a function of the pressure, the pressure we're applying, the background pressure.

And so we know what pressure we want our rocket engine to operate at, our microtube, chemical thruster to operate that. And then we can look at the corresponding linear burn rate. And now we know how fast we have to feed propellant in to counteract the upstream burning of the propellant. So we've taken these fundamental studies and we've fabricated a prototype thruster that can operate in the chemical microtube mode and the electric electrospray mode.

And down here in the bottom, if you can see it, this is a photograph of the very first prototype we've fabricated here. Propellant comes in from the left, this propellant inlet. And then this block right in the center is an array. It's an array of these microchannels, couple hundred micrometer diameter microchannels. So when we heat the block and feed the propellant in, we get this chemical decomposition.

And that's what you're seeing in this middle video here. So here's the thruster and we're heating the thruster up. So it's preheated and then we feed the propellant in from the right. And if I can stop this at kind of exactly the right time here, what you'll see is this nice plume. You can start to see this elongated plume of the decomposition gases being formed and being expelled out right here. Now, if I let the video play a little bit longer, you'll start to see the smoke just kind of goes everywhere. There's a liquid dripping out. And that's because as the cold propellant flows into the heated thruster, the cold propellant cools the thruster. And so now, as the test progresses, the thruster is not as hot anymore. And so now it can't decompose the propellant. So now you start getting liquid leaking out the end, dripping out the end.

In our future experiments, we're going to continuously heat the thruster so it maintains its temperature. And you constantly get that kind of nice developed plume structure that you can see in the early time of the video. On the right side over here is same thruster. Actually, it's not quite the same thruster, it's a cousin to this. It's an identical cousin or sister to this thruster, and it's being operated in the electrospray mode. And so what you can see right here, these black triangles, these black triangles are the liquid, the propellant, the propellant being electrostatically extracted out.

And you can't see the droplets or the ions, but they're there. We can measure them, but you can't see them because they're too small. You can't see them in the video, but these conical structures are what are called tailor cones. And this is the shape the liquid meniscus takes on whenever you're applying a strong electric field to it. So you form this point, the sharp point and ions and droplets are being extracted from that sharp point in this electric electrospray mode.

Our research right now is continuing to focus on the thruster development, doing tests like the ones shown in these videos here. We're also moving on to thinking about how to take this prototype thruster and put it into an actual propulsion system. The propulsion system's not just the thruster by itself. You have to have the feed system, the propellant feed system, like the propellant tank right here. And the pressurization system. So this is an inert gas that pressurizes the liquid propellant tank, such that when you open this valve or these series of valves, propellant flows out through these tubes into these four thrusters shown here.

Something else we're working on is the power processing unit. Being able to develop a power conversion electronics that will take the spacecraft bus power and convert it into a form that's usable by the thruster. We got to take the spacecraft bus power and use it to either heat the thruster for the chemical mode, or use that power to create the electric field that will do the electrospray that will extract those ions and droplets for the electrospray mode. All right, with that, I'm going to finish up here and I will take any questions.

Danielle (24:33):

Thank you so much, Dr. Rovey. If anyone has any questions, you should be able to unmute yourself. Now you may also submit questions in the chat.

Dr. Rovey (24:44):

Yes, please. Go ahead.

James (24:45):

Yes. Just wondering, how has your research so far been used in today's current space precaution systems and how has it been used so far?

Dr. Rovey (25:00):

Right. So the propulsion system we've been working on right now, this monoprop, microtube, electrospray propulsion concept, we're working closely with NASA to develop this concept. And NASA is currently doing some mission studies, lunar mission studies to compare this propulsion approach versus more conventional or standard approaches such as just a purely standalone chemical propulsion mode or a standalone purely electric propulsion mode, looking at the mission scenarios where this multimode approach provides you the additional, like I said, flexibility and adaptability to enable either new lunar missions or to reduce the mass, to reduce the propulsion system and the spacecraft mass for lunar relevant missions.

And it's really tied in with NASA's Artemis program and NASA's interest in returning to the moon, they're envisioning using small satellites, CubeSats, small sats, hundred kilogram class satellites and smaller to assist, enable, enhance Artemis, lunar type missions. For instance, using small sats to provide communications or communications relay to provide reconnaissance or lunar mapping, mapping of the lunar surface. And there's even interest in using a propulsion like this for small satellites as sample return missions, either potentially launching from the surface of the moon itself or as being sort of a leeway station between lunar orbit and then the return to earth.

You can imagine a vehicle that gets gets the sample off the surface, and then rendezvous with perhaps a multimode propelled small sat in lunar orbit, which then transports that sample back to earth. And now there's perhaps a reentry type vehicle or capsule on board that's then jettison and reenters earth's atmosphere. So these are the kind of the scenarios that NASA is interested in relevant to the Artemis and the return to the moon where multimode propulsion and also just small sats in general are envisioned to play a role.

James (27:41):

And James had another question. Does the electrospray mode give more finely tuned, but slower maneuvers compared to the chemical decomposition mode? Or can both modes produce equally fine maneuvers?

Dr. Rovey (27:55):

Right. So the electric mode would provide a finer control just because of the lower thrust, the smaller impulse levels that can be provided by the electric mode. And so it would be more conducive to fine maneuvering. The chemical mode you can think of it as more for a course maneuvers or course corrections, if you will, the higher thrust, higher thrust, lower ISP, but for more timely maneuvers as well.