Physics Lecture Series

April 2, 2018

Shaun Stewart

>>DR. GARRISON: All right. Can I have everyone's attention? I would like to introduce our speaker today. This is Shaun Stewart. He is from Intuitive Machines and you guys have met a couple other people from there. I guess he has recently been on a world tour. Today he is going to talk about using physics and video technology to make a training simulator. Just a little bit of a background. He is a senior development engineer at Intuitive Machines here in Houston. He received his bachelor's and master's in Aerospace Engineering from the University of Texas in Austin in 2004. For approximately 10 years, he has been working at NASA modeling spacecraft navigation system, testing, and developing navigation flight software in simulated flight environments for manned spacecraft. Since joining Intuitive Machines in 2014, he has enjoyed applying skills and techniques for physics modeling and simulation used at NASA for problems pertinent to the oil and gas industry.

So it seems to be an exciting talk. I will hand it over to Shaun.

>>MR. STEWART: Thank you Dr. Garrison. I just got back from Canada and we were doing helicopter testing with Doppler radar technology for survey in Antarctica so that's another project maybe we will have a chance to talk about maybe next year.

So for those of you that were here prior two weeks, my colleagues gave talks on work we have done and (inaudible) gave a talk last week about our reentry vehicle technology for returning vehicles in our space station to the earth. Today I will talk about technology that we have taken basically from your experience at building training simulators for astronauts at NASA and trying to apply that maybe that capability of use for oil and gas industry.

Specifically, with respect to horizontal directional drilling and so this is a little different than drilling for oil. This is basically companies that run, for example, river crossings to install drain systems, water conduit, electrical conduit I approximately 100 feet into the ground, 2 to 3 miles from entry to equity. So it's a much more precise operation and simply trying to just a reservoir of oil in the ground. So basically, they are trying to stay within accuracy of matter of feet drilling mile and a half away, only looking at basically pressure gauges and some survey that they have available to them on their equipment.

So I will give background to Intuitive Machines and work we have done pertinent to this technology and give an overview of the problem with horizontal directional drilling and talk about our solution for basically allowing drillers to practice this operation in assimilated environment in real time. And then finally I will open up to questions if there are any questions.

And so essentially what we are talking about is real time software working with hardware in the loop with humans in the loop interacting with the system and it's a safety critical system. So it's very imperative that any failure in this system can be catastrophic whether -- in this case, in the oil and gas industry, not only -- since they are trying the make money and doing this job effectively and efficiently but you also have machinery and a group of 10 to 12 people who are operating hands on with this machine and if something goes wrong can cause significant damage or seriously hurt someone. And so the way someone becomes a driller today is they basically get hired and they watch, observe the operation for two years and after some time they get some matter of minutes on the equipment and over the years they develop enough confidence and they allow someone to become the driller in the process today. So we are basically looking to take technology we used -- we developed. This is a picture for Orion, a cockpit simulator to basically run the Orion software for entry and orbit and different scenarios. Running the flight software and looking at displays that we will see when they get in space and operating controls that the actual controls hardware in the loop, running simulation real time. So this is in building 4 on site at JSC.

That's running in coordination -- basically in the back room they have mission control., running flight software on the flight computer. It is driving the displays and parameters that the astronauts are seeing, and you are able to run through all sorts of scenarios and practice and issue fails and see through all of these different scenarios that the astronauts are on board and handle any issues in control. So that's a good analogue for what we are trying to do for this problem.

So here, to give you a sense of scale, this is a drilling rig and it can pull a force of 1.3 million pounds and so the way a job works is this is one example where they basically do a pilot hole from one end and do a river crossing in this case and precise requirements of the depth they need to cross underneath this river and come out and there is a specific point on the other side they are trying to equity. The range from entry to equity can be anywhere from 800 feet to 3,000, 6,000 to 3 or 4 miles. For distances over 2 miles, they will have two rigs. One entry point at both ends and they will meet in the middle and bump bunts in the middle and then pull the pipe through. The pipe diameter can be in excess of 60 inches in diameter. So you can imagine how much energy it would take to drag a 60-inch pipe through a hole 2 miles long. There are enormous stresses in the system when they are drilling and then you have people that are basically working right there on the rig. So accidents can and do happen.

So we're basically trying to improve the operation, not only in just execution of the hole, the performance of the hole, but also in educating the driller on what to expect when interacting with other people on the rig. Another complexity -- this is a CAD model of the bottom whole assembly which this is the final, on the very end of the pipe there is a 30-foot nonmagnetic drilling collar and on the other side of this you have hundreds of just standard drill pipes that are approximately 30 feet long. The reason it is not nonmagnetic is because you have a sensor pack that's right where the steel pipe can interfere, so they have a special drill collar, so they can get good data to accurately know where they are under ground.

And the way they steer is this -- you can't tell on this scale but there's a slight bend in the piece and so they basically can orient that bend, if they oriented it up and push, then they are drilling, and they are going to climb the angle. They have the ability on their gauges to know how that bit is oriented underground, however far away.

This equipment here, in this scenario this is a fixed piece of equipment that they use in drilling in sand and a jetting and they basically have a jet and they force about 300 gallons per minute of drilling fluid out of this hole and it blows out and the debris gets circulated behind the drill pipe. When they are drilling through rock, there is a slightly different configuration where they use a mud motor and it's a starter and rotor piece and they force mud through the rotor and it forces the drill about it to spin. It is 30 feet long and the probe is back in this area. When they are drilling in rock and make a mistake, for example, and the rate of penetration can be 10 feet an hour or more or less and if you get off course, basically you've drilled 30 feet past where you are trying to be before you know that you are off. I mean you have to pull this out and try to correct in hard rock and so it is really important that they are able to have sort of a sense of -- by looking at the measurements at any given configuration they are getting that this is back away from where they are actually working and it may take them some time to realize how bad they are actually off right now.

So basically the problem is to build simulation, we're modeling real time the physics of drilling through rock and sand, using this type of equipment and we're interested in modeling the orientation of this bit so that you can know if you are pushing, which way you expect to go. Also we're basically modeling -- basically modeling is a function of how fast you push, how hard you push, and the amount of volume of mud you are circulating and the type of rock that you are drilling in. What's your rate of penetration that you expect to see? And then if your rate of penetration changes, do you understand why? And it can be unexpected geology or an issue with the machine.

We're also modeling the dynamics of the drill string and so we can have hundreds of these you know, 30-foot steel drill pipe in the ground and as stiff as they may seem, they do and will deform underground under high forces and torque. So we're modeling and capturing the deformation of the drill pipe and the bending and twisting of the drill pipe and it can be as much as where basically when you turn the drill at the rig, you can have as much as a degree of twist in your drill pipe for every thousand feet so it may take a while for when you turn for the bit to respond. So that's why we're basically measuring the orientation of the bit right here, so they can know -- even though you are maybe turning the rig up hole, it might not be turning at all. So their performance or ability to finish a hole depends on how straight it is.

If you have a lot of variations, then it can be difficult to pull a pipe through a hole that has lots of -- the term is tortuosity. If you are trying to turn, the tortuosity of the hole will come in contact with the pipe in more or less places and we are trying to measure the friction they see when they are rotating and sliding and getting a realistic response of what they expect to see in if field in different types of geology.

Another important factor is the rate of debris and regeneration. You are having different debris of different sizes depending on the configuration and geology. If your mud flow rate is not appropriate then those articles might not come out of the hole and it can clog the hole and you can if you create a closed volume and you are pumping high pressure fluid in that volume and it is going to find the path of least resistance but sometimes it is straight up to the surface and so that can cause basically a degradation and it and scrap an entire project and you have to start over.

And then finally trying to model the characteristics of the measurements that they expect to see. All measurements are, by nature, imperfect and so we are trying to make sure that we account for those types of sensitivities, so it gives them a realistic factor to take into account. Okay.

And so this is what we have done to solve this problem, we have horizontal directional drilling simulator with the ability to configure the type of rig they are using. I showed stats for the 1.3-million-pound rig, but they have various ones depending on the job. Here on the right is an example of their control panel and we have taken an actual control panel that was provided that they use on the job and wired it up to our simulation server so that the driller can practice with the actual hardware that they use to drive in the field. And then taking those signals and processing them through a real time analogue digital conversion of the push and pull controls and the clamps for connecting and disconnecting the pipes, controlling the mud flow rate and looking at basically those pressure gauges which tells them what is going on with the rig, and putting that into a physics model of the rig up hole and the drilling operation under ground.

So I'm going to go through -- I think one key theme throughout the talk is that the dynamics and the physics of modeling, drilling underground is very, very different than actually in space so this was a big challenge. The basic principle of development of software for hardware in the loop real time systems but we had to expand our ability to model these types of physics, these types of interaction of drilling and cutting and jetting and rock and generating and circulating debris and modeling friction and deformation of miles of pipe. So we used open source tools and they were needed to bring in capabilities that we did not already have to solve this problem.

So the first major piece is a multi-physics simulation and analysis engine. This is also what we used to solve the subsea -- the dynamics with the subsea (inaudible) column. It's a multi-body dynamics simulator. It can run -- basically it is designed to run complex machines and mechanism and we can do the dynamics and kinematics of the system using an open line (inaudible) architecture and apply forces and torques to elements in the system and it will solve for constraints of the system. Basically the validated tool that allows us to go and focus on other elements like how do we model the rate of penetration through rock? Those things that we had to go do research to figure out how to model.

Finite elements is another one that we knew from the start that traditional finite element methods were not fast enough to model the deformation of a system on this scale in real time and so we've used a finite element analysis method from this tool that allows us to look at large information and time stuff and capture the expected response to sufficient validity in real time.

Also basically allows us to parallelize the problem and so we have broken it up and running this problem parallel across 35 processors and are using basically -- basically splitting the computational load across the views to get this job done. This is also made possible by this tool. And then finally a big part of this is, you know, they're interested in connecting pipes together and collisions underground and so the collision model is handling when you connect two pipes together, screw them together, applying large torque to make up a joint, the physics of that operation is critical and so we use collision detection with this tool. So this is a -- this is just a standard excavator, but this is called a deck hand, a pipe gripper and it's basically a special tool that's made for this type of work. It allows them to grab a pipe and put it on the rig and so we developed, based on CAD measurements basically, a 3D model of this machine that we're using in simulation.

Here's an example simulation from the tool showing the FEA and basically -- basically this is a model of a tire rolling through granulated earth and you can see it is capturing the deformation of the tire and interaction with basically a pile of particles on the ground. So this fundamentally is that capability that we need to be able to look at capturing the deformation of a 3D mesh and interaction with the material. So basically, we broke up the software problem into a multi-threaded application and we are running natively on Windows and that's important because a lot of the tools that we pull in these open source tools are being developed in Windows. Traditionally, all of the work at NASA is done Linux and other critical types that are not normally widely used. So we adapted and made your developmental environment in Windows and the tools that we use work well in those testing environments and it allowed us to quickly learn how to use those and run their tools and their demonstrations and tutorials and pull these tools in. We broke up the application into several threads.

There is an uphole rig model which basically is the model of all the machines that you see in this uphole graphics. This is to make and break joints and this can slide up and down a rail. This will hold the drill string fixed and this will twist the free pipe relative to that and force them to make basically a super tied joint so that when you have mile of pipe underground, you happen to put a high -- anti-torque that you won't have an active separation. You won't go halfway down and loose half of your drill strength. One of the things we are concerned with is how tightly these joints are made. Every joint. They want to make sure that the driller is aware and is making those up every time otherwise you can lose a lot of expensive equipment under be ground or have to spend a week trying to fish it out and connect to it and pull it out.

This is the carriage and it allowed them to bring in new pipes and spindle up top connects to the pipe down blow. This is a decking gripper that I described, and it is gapping pipes off of the stack and bringing them into the system. As the drill is putting pipes back in and pulling out, it will stack it. So that's all basically the mechanics of all of this interaction here all the way down to 60 feet in the ground is part of this model.

Then we have another and that's modeling the down hole drill pipe modeling and that's what you see here. There is a control volume that ends 60 feet underground and goes all the way to the beginning of that beginning of that nonmagnetic drill collar so the deformation and the friction and everything that's happening between the rig and the drill bit is being modeled in that thread. They have control volumes that measure the constraints and they exchange information over shared memory in real time. Then there is another thread that's basically just modeling the drilling and orientation of the drill bit and the high pressure jets relative to the end of the bore hole, basically the impingement between the jet, the expansion of that jet and pressurized volume in front of the bit, the impact and angle and basically the erosion, the depth of penetration that we expect to see through jetting, through pushing and turning as it is grinding through whatever is in front.

And then we have a real time event receiver and so this is the piece that essentially is monitoring the control panel, the hardware control panel and we have essentially a hundred signals, maybe 120 they can use and updating those to the closed control system models that basically try and drive these carriages to the target velocities or forces or whatever is being commanded on the control panel. It is used also once we kind of run the whole sim, the dynamic step, when we get the result of each step, then we take measurements of what they should expect to see on the hardware gauges and also on virtual gauges on the applications thread and update for them to see every time step.

There is a graphics threat where we have leveraged another tool that has been developed and it is for the video game industry and it is called Unreal4. There is a couple of different platforms you can to develop video games and this is a primary run and it is something of a revelation that they are really pushing the edge of what we can do with our engineering tools and we found that by pulling in some of these capabilities being developed for video games and money and energy put into that, that some of what they are modeling is very realistic and more than what we can do with our engineering program. So if they have high pressure mud in the drill pipe and they break the connection with the spindle and you get this spewing of mud out of the pipe, remodel that entirely using Unreal4. We are not interested in and it is not critical, the actual flow and response of that material but it is important for the driller to have an intuitive sense that there is a high-pressure fluid there and so the fact that they can have it impacts services and having the velocity of the pressure, relevant response it is beneficial to be realistic. It is a useable capability there.

There is also a down hole and this is more detail about the drilling and jet willing model. We used another open source tool for a Dreamworks' animation and it is VDB, video database. And it is a tool for manipulation of sparse volumetric data and one example is we are trying to capture the geology of the ground we are drying through, this infinite volume of earth that we want to interact with, it shows you how it efficiently captures that for that volume of data. So when a this is one big volume that they use to capture the properties of this entire space. Then in this area with more detail, they break it up automatically into smaller boxes to capture it efficiently, the data needed to represent the state of that system.

So we use this open VDB tool to capture the geology of the earth we're drilling in and also when we are generating a bore hole, we capture it in real time, the generation of that space. And here we can -- this is obviously not realistic but to demonstrate, as we are drilling we capture sort of a delta space that's interacts as a function of our erosion model and it generates a rock slide space that is sufficient to capture these places to define the bore hole. We can create a level set and we can create a 3D model to capture and this is in turn, part of the boundary condition that's passed into the drill stream for computing the friction of the entire -- the history of the drill hole. So we can see how tortuous this hole is to see how far we can push through it would fail.

So this is an example of a drill hole that we did with the drilling simulator and you can see the size of the (inaudible) here and it breaks it down to capture that. Basically the boundary of the hole as it is written.

It works amazingly quickly and so that was just a capability that's out there for the movie industry that we were able to pick up and use in a matter of weeks. I mentioned earlier the drill string dynamics model and we and we use the absolute nodal coordinated frame element. It is a nonlinear method that allows us to have large elements and so we break up the pipes into 3 or 4 elements, 10-foot segments essentially that can be formed and have significant deformation at a time step that have semi realistic. By doing this, it allows us to model the deformation of these pipes in real time and capture an expected response.

So the ANCF method will capture bending in 2 dimensions so say vertically and laterally and then we have -- in between two segments we have incorporated a torsional spring that allows us to account for the torsional deformation we expect to see. And then calibrating and tuning the constants for those models and dampers that represents basically data from the field, so we just calibrate the specters.

I have some videos here that are kind of representative of that. Let me pull them up real quick. So you are viewing under be the covers here and we are looking at our simplified model of what's underneath the graphics and so this is just a block that represents the carriage and the spindle on the rail and we have our inclined rig here and this is a system of wrenches. So here we have a pipe in the deck hand waiting to be added and there is one in the rig connected to the spindle and so we are able to connect the spindle to that free pipe. We drill it down and push it through down in the hole. Unscrew and clamp it with a clamp and unscrew and continue. So here you can see we're basically tying that joint together and sliding both pipes into the ground.

Here's an illustration of basically the -- this is a single 30-foot pipe and we have broken it up into segments, ANCF elements with blue and white cylinders and we have implemented a torsional segment here, so we can capture torsional deformation of that individual pipe. Then we connect these system of pipes together and we are able to accumulate effects of I-forces and torques on a drill string.

That's the one bending and I think we get a little -- nope, that's all you get. Okay. All right. This is interesting.

So for a driller, the operation of connecting two pipes together is of critical importance so spent a lot of time on trying to figure out how to accurately model the physics involved in screwing two pipes together. So you have the bend on one pipe and the box of another and if you slam them together, there is going to be a collision and if in order for you to screw there has to be basically relative rotation and the relative translation of those two pipes is sort of constrained by the pitch of the screw.

So here it's sort of a demonstration of two pipes so we slam them together and then as you rotate, they are able to pull together until finally they are fully screwed together and then after they are face up, then what's of critical importance is how tightly those joints are torqued together after they have -- they can no longer be screwed any longer. If you have a pipe that's made up and it takes a significant torque to -- you cannot (inaudible). There is several states of collision and constrained motion throughout all of that -- that's of critical importance and we do all of that with this simulation engine that we use to model the drill string.

Here is kind of an early accumulated drill string looking at trying to calibrate the nature of these elements and the springs that connect them and looking at expected response at the end of miles of drill pipe and calibrated this to expectation.

Okay. So here is a picture of the hardware control panel. And so there is controls for the engine. There's   this is a control for the carriage and the rotary and this is controls for the wrenches. There's a fixed wrench and fixed clamp and wrench clamp and clamp up top. There are presets they can use to make sure they don't exceed the limit of the maximum torque or force they want to apply and these are the hardware gauges we can use. They can look at the amount of PSI they are putting in the hydraulic system that they are seeing as they are working. In addition there is an external mud pump control, and this basically controls how many gallons per minute of drilling mud are forced through the drill string and this is a virtual gauge that we developed that tells them the inclination and azimuth and tool face which is essentially up and other things like pressures and temperatures being controlled underground.

So we have a system of analogue and digital converters and I talked about this already but for completion, so we pull wires from this system and the -- we are monitoring at high rate and real time and captures states of this entire system, putting it in shared memory that is basically being sampled by the uphole model you know, every time it runs a cycle.

So these things are essentially asynchronous where the event receiver is running as fast as it can all the time updating the current state of this at 100 hertz or 200 hertz and running our dynamics probably 10 hertz in terms of the entire cycle, what's happening.

For the 3D graphics and the modeling of this system, a lot of this was interesting because what the rig is and how it works, a lot of information is proprietary, so we had to surmise from the rig that is provided common knowledge, videos of the rig and operation, and implementing 3D models of this system in CAD. This is done in another open source tool called Blender for modeling the deck hand pipe gripper that they use in this job. So building 3D models of all of this equipment and modeling the hydraulic controllers that drive the carriage and the wrenches and basically give outputs to the pressure gauges that tells them what's going on with the equipment so that was a large part of the work, trying to understand what the system is and how it works and how to model it.

At the end, here's essentially what we developed. So here you can see, this is our customer this is what they normally see and in reality, it is a lot messier than our clean graphics picture of the world. But they are able to sit down at the act control panel that they use in the field and run and drive and look at basically assimilated view of what they expect to see when they work on a job. This enables them to train and evaluate a driller's ability and performance to execute a plan effectively.

It also -- you know, they are able to throw in the safety issues or issues with the rig and make sure that the driller can recognize that there is a problem and respond to it appropriately. So in summary, what we've done, we basically pulled in our expertise working in the aerospace industry and applied it to the oil and gas industry and we have done that by leveraging tools outside of our experience and even outside of our industry and found capabilities that are developed for the gaming industry, for the movie industry that are relevant to high fidelity engineering analysis modeling simulation. And enabled us to solve a problem that we otherwise would not have been able to solve. The ability to model this system in real time was a significant challenge and without sort of the advances and capabilities that are being move forward through these other industries I'm not sure it would be possible for us to solve. All right.

>> (inaudible).

>>MR. STEWART: So they are using a magnetometer underground to detect the magnetic field where they're heading and so they have basically a survey of the expected magnetics in the ground before they start the job and they are using that to navigate while they're drilling and so they have basically a wired sensor that runs all the way up hole to the rig and getting real time data from the magnetometer underground and they have a gyro that gives them orientation of the drill bit.

>> (inaudible).

>>MR. STEWART: Well, I get to go and observe on a few jobs and I think it can take the operation of drilling -- they have sort of a couple of phases of a project which is drilling the pilot hole and in this case, they have essentially a 9-inch bit and they make a 9-inch hole and then they have to come back and increase the diameter of the hole. They call it reaming. So increase it to 15, 20, 60 inches, whatever. They have a reamer that they run through there and they have an existing hole. Drilling the pilot hole is essentially their first challenge. So they have a reamer that someone can come and practice for a couple of segments.

Once the hole is finished, they run a swab and clean it and then the final phase is pulling through the pipe through the entire hole. So assemble a pipe above ground miles long under be ground and drag it under the hole once it is finished. I got to see a job in South Carolina where there was an issue that there was an old pressure vent in front. They were not basically properly cleaning the hole and they are fracking out all along the way and then they finished the hole finally after lots of issues and trouble and then when the pipe got halfway through the pipe broke and they had to start over. Yeah, I think the cost of that I think it was about $2 million to start over.

Certainly, you know, I think it's -- I think the way that things are done now is kind of you know, they take time to train people up, but I think things are allowed to happen and they have to fix them after the fact.

>> (Inaudible).

>>MR. STEWART: It could be for sewage or electrical or water and all kinds of it is not necessarily for oil and gas. So this -- there is kind of an analogue, directional drilling for oil and gas where it is more like incline drilling. This is literally horizontal drilling so it's a big stress on the drill pipe because the entire length is laying on its side in the ground, so you have a lot more friction verses drilling vertically.

>> (inaudible).

>>MR. STEWART: A lot of times, like the one I went to was a protected marsh, rivers.

>> (inaudible).

>>MR. STEWART: You can go hundreds of feet under the ground and not affect the environment there.

>> (inaudible).

>>MR. STEWART: Yeah. (Laughing). No, that's why I want to make sure it is done right. But I think that's an appropriate observation that sometimes mistakes can be catastrophic, not only to the bottom line but also to the environment that you are working in.

>> (inaudible).

>>MR. STEWART: We're mainly focused on trying to model the physics of what happens with geology and their customer is taking this and developing a training program and integrating it in their operations, so we are not involved with that aspect.

>> (inaudible).

>>MR. STEWART: Yeah, part of our research and development group, you know, we have some effort, some time that we spend in evaluating new capabilities and that's things we do in advance. There is a lot of risk in pulling in open source tools into your product line and so we have process for evaluating those things using robots and automated tests and basically making sure that the tool always works as we expect before we try and use it in the pilot. But because the user base for these things are so enormous, there is lots of tools, lots of resources out there for solving issues and lots of people you can talk to, to get help so it can be a significant leg up whereas for, you know, high fidelity modeling of the gravity of Jupiter and mercury and that's like 200 people and especially if you find a problem nobody has seen before.

>> You said people have been using game hardware for doing these performance simulations so (inaudible).

>>MR. STEWART: Actually the (inaudible) has a flex engine that integrates well with the Unreal Engine 4 and it drives that like the fluid flow and we're able to capture the mud dynamics up hole.

>>DR. GARRISON: Any other questions. All right. Thanks to our speaker. (applause). Next week's talk we will have (inaudible) from LPI going to be here talking about weather on the moon so I guess I'll see you guys next week and if I have not gotten your papers from last week, let

me know. Also I checked with the grad students on your projects.

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