Biomechanics
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Lecture - 82
IMU Based Full Hand Kinematics Measurement System (HKMS)

Vanakam, welcome to this video on biomechanics. We have been looking at measurement of kinematics, body segment kinematics in the human body using specific systems we wanted to check how we can use IMU's to measure finger segment angles.

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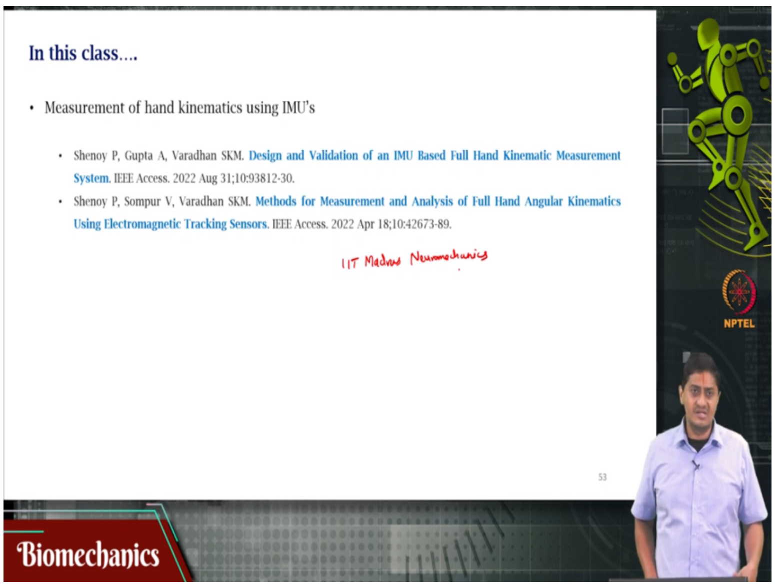

So, we continue that discussion, so in this video we will be continuing our discussion of these papers by my PhD students Prajwal, Anurag and Vignesh. For more details of this work on more of this kind of work google our lab web page IIT Madras neuromechanics, google this and find our publications. So, in the last video we looked at how we can measure the kinematics of a single finger and represent that kinematics in real time or render the kinematics in real time using some modelling software like for example **(()) (01:41)** or unity.

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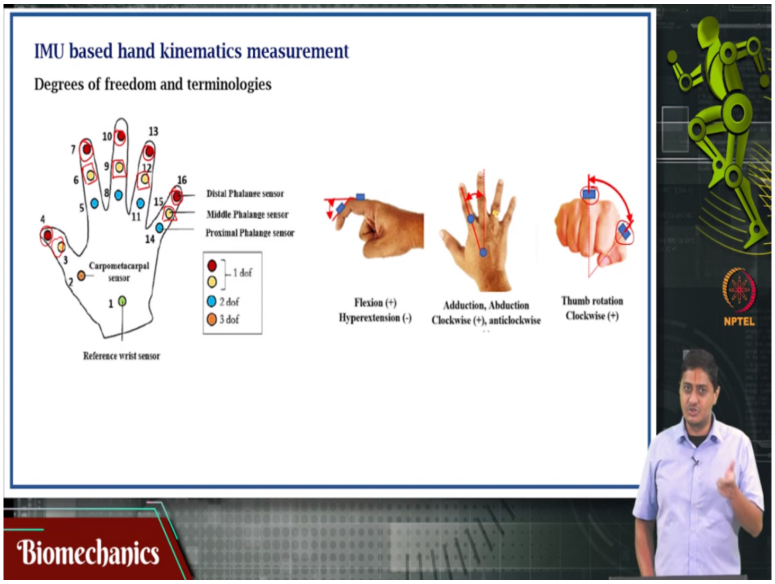

Here we discuss how we can use similar principles to measure full hand kinematics. How many different sensors would you need and how many degrees of freedom would your model have. So, remember the distal phalange only fluxes and extends, the middle phalange also the same. So, essentially the dip joint or the distal interferential joint and the pip joint or the proximal interferential joint are modelled as hinge joints or one degree of freedom joints.

So, this one degree of freedom joints are all marked in red and yellow, all the sensors on the distal phalange are modelled or marked here in red and all the middle phalange sensors are marked in yellow. Actually, in the thumb you only have two phalanges you have the proximal phalange and the distal phalange. So, these two these two segments and then you have an extra special sensor which is the carpometacarpal sensor, we will come to that in just a little bit.

So, the yellow on the thumb represents the proximal phalange. These are all are these 10 sensors are that is the red sensors and the yellow sensors are all one degree of freedom are required to measure only one degree of freedom. What are these? Flexion, extension hyper extension, well hyper extension does it happen well it does not happen voluntarily but I can apply an external force and make the distal phalange to hyper extend a little bit like that I can push this happens when you are applying a force on an object.

When the force exceeds a certain limit, your finger will start hyper extending your distal fronts will start hyperextending. So, fraction extension hyper extension is one degree of freedom and then the metacarpophalangeal joint, remember in the previous video I mentioned this even in our anatomy class we have mentioned this. The metacarpophalangeal joint is a two degree of freedom joint it has it can do this flexion extension and it can also do that abduction adduction.

So, abduction adduction is the other degree of freedom that the proximal phalange are the proximal phalange sensors are required to measure. So, the proximal phalange sensors for the four digits index middle and ring and little are two degrees of freedom sensors, there are four of them. Of course, the proximal phalange in the thumb is a one degree of freedom because there are only two segments in the thumb and then a special sensor is present on the carpometacarpal sensor.

We call this is a three degree of freedom sensor because I can measure this, I can measure this and I can measure this but there is a problem when I am placing my hand flat like this, there is naturally that is a variation in the angle between the where the carpometacarpal sensor is located and where the wrist or the reference sensor is located. You need to have an idea of that also that is a normal here and there is a normal here.

And if you want to measure the rotation you need to have an idea of the angle between these two normals. So, your wrist sensor is crucial in finding the measurement or finding the orientation of the carpometacarpal sensor. So, your carpometacarpal sensor is a special sensor. So, how many sensors do we have? Well three each finger has three sensors, so 5 times 3 is 15 and one wrist sensor, you need 16 IMU's to measure your individual segmental orientations or angles.

Among these you have about 10 one degree of freedom sensors or 10 sensors measure only one degree of freedom. Four sensors measure two degrees of freedom, one sensor is a reference sensor and only one sensor measures three degrees of freedom that three degree of freedom sensor is the carpometacarpal sensor of the thumb. So, these are the various sensors that are required to be placed under fingers.

Note that it takes time to instrument the hand with these sensors because you need to place the sensor and you need to you need to find a way to attach the sensors to the fingers. You can use surgical tape, some method, double sided tape works but in fast moments the sensor might slip. So, you might have to innovate there and find a combination between surgical tape and double-sided tip you might have to use both also.

Something that you learn only by experience our lab is relatively well experienced regardless of whether we are equipped or not we are well experienced in this art. So, we know how exactly to place the sensors, a kind of innovated around the methods of placing sensors. So, the instrumentation time if you are a newbie, it will take 45 minutes to one hour our lab students my PhD scholars, PhD scholars who work with me in our lab they are able to instrument this in about 20 minutes 15 to 20 minutes.

Because they have the expedition, they know what are the things to keep prepared for. So, they keep this the tapes ready, they keep the sensors ready as soon as the participant comes, they just attach. Sometimes two students work in a coordinated fashion synergy to make this happen. Beyond this level it is not possible to minimize the instrumentation time well it may be possible but at least we have not found this where we are still working on it.

Remember human experimental time is a valuable thing, it is extremely hard to find human participants and get experimental time with them. So, you need to find a way to minimize the amount of time it takes for instrumentation and maximize the amount of experimental time, so that is always a challenge as experimentalist. In particular a challenge in human experiments because there are ethical constraints involved.

Consider this because there might be biological needs for the human participant. So, you need to finish your experiment before a need for some biological urge comes up, so maybe they are thirsty then you can give them water but there are only so many things that you can do for them. So, there are challenges, so we need to find a way to minimize the instrumentation type and we are working on that it is a continuous process.

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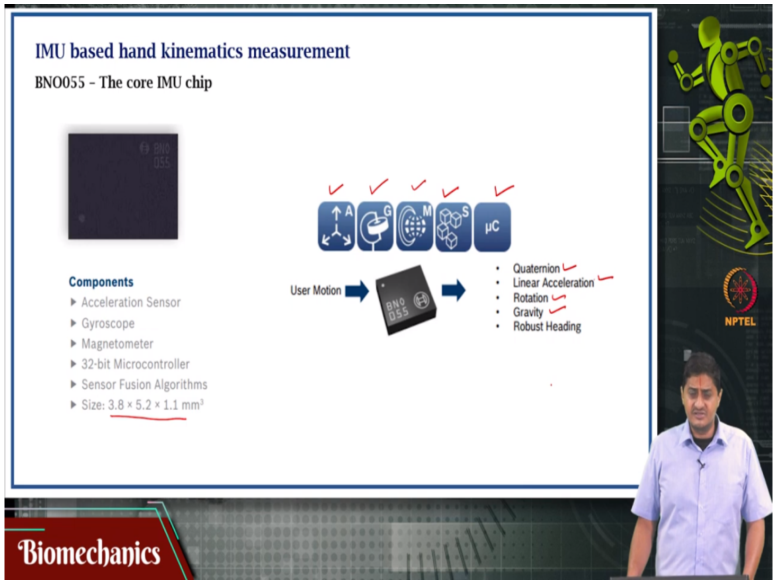

So, this is all fine, what is the particular method that we use? We use the Bosch BNO055 IMU chip and we built our own board. So, in our lab we have developed our own board around this Bosch BNO055 chip and developed the instrumentation around this chip this is not an advertisement or an endorsement of Bosch BNO055. You can use any IMU you want and any microcontroller you want.

I am only describing the method that is used in our lab and I have to mention the specific method all the details and that includes the particular IMU which is Bosch BNO055. What does it have? It has an acceleration sensor well it is an IMU so it will have an acceleration sensor it has a gyroscope. What does a gyroscope do? Measures the angular velocity under magnetometer, specific to Bosch BNO055 when compared with other IMU's Bosch BNO055 has its own microcontroller.

This is unique and this is very important because it has its own microcontroller it can implement and run its own sensor fusion algorithm; it comes with hardware implementation of this sensor fusion algorithm. And it turns out Bosch says that this sensor fusion algorithms are optimized for measurement of human movements this is unique because this is important because your sensor fusion algorithm must take into account what is the application that is used.

Here we are interested in measuring human movements and Bosch says that this sensor fusion algorithm is optimized for human movements we will have to take them we will have to take this information for what it is worth. We do not know the details of this algorithm because it is implemented in hardware and is probably proprietary that Bosch will not want to share the details, so obviously.

So, this is already implemented you just have to set the parameters you just have to give some details that you need to plug in into this microcontroller and then it will run this algorithm and just give the output as the quaternion that is it. It is a very small chip that is important, sizes 3.8 mm 5.2 mm by 1.1 mm this is the size of the chip not the board this is the size of the chip. We need other components to measure.

So, there will be a printed circuit board that will be built around this chip that is going to consume a little bit more space we will come to that in just a little bit. So, what does this Bosch BNO055 do? It measures acceleration it provides gyroscopic data that is angular velocities provides a magnetometer. And it has this unique probably proprietary sensor fusion algorithm optimized for human movements.

And it has its own microcontroller and it can output linear acceleration rotation the direction of gravity and quaternion’s and its relatively robust. So, these are the advantages and these are the features of this particular IMU. There are other alternatives available this is not an endorsement of Bosch BNO055 a as I mentioned but the challenge is that they may not have their own microcontrollers.

So, you will need to implement the sensor fusion algorithm in your own microcontroller and you need to develop the algorithm yourself which you can do that is likely to be more sensitive to the particular application if you know what you are doing. So, that requires some advanced skills in terms of coding and in terms of understanding of your own problem. So, there is no one size fits-all solution.

The solution that you want depends on how much you want or how deeply or how badly how desperately you want that particular solution, how much investment are you willing to make not in terms of money in terms of effort in terms of time and other resources. So, there are challenges for everything. So, there might be limitations also because if you want to measure from multiple segments simultaneously like we do in this case 16 segments simultaneously.

And if one particular microcontroller will have to perform sensor fusion for all the 16 that has to be a very powerful microcontroller. So, there are challenges there are limitations and challenges in terms of what we can and cannot do using different this. So, there is no one size fits all solution. Here we just describe what we did. So, it is a relatively small chip that we built around which we built a PCB and this.

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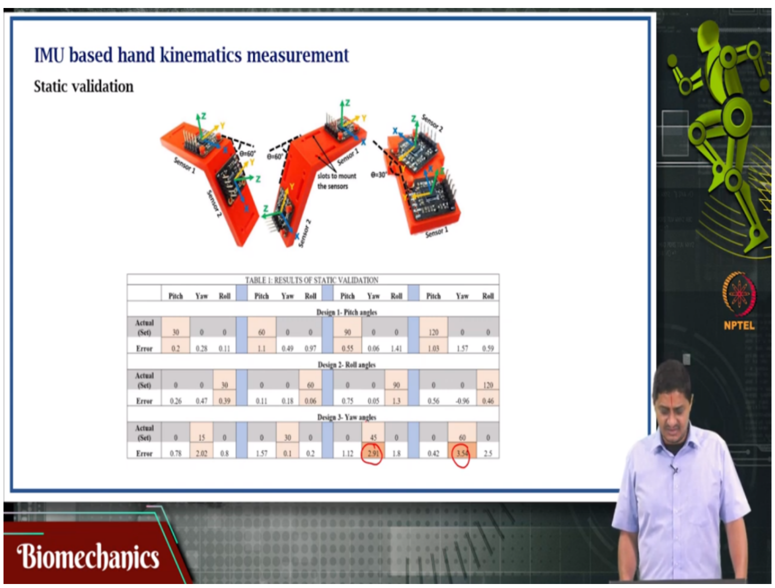

So, to start with we just purchased some boards off the shelf that used BNO055 at its core. So, we did not build it initially in the initial stage we just purchased it off the shelf because when you are testing these things it is best that you test with something that is already available as opposed to reinventing the wheel. Once you know that something is working then you can build for it. So, this is a test to decide whether you want to invest the time.

So, we performed a static validation using off-the-shelf boards that are already available and we 3D printed some frames that had known angles. So, these frames have known angles between two segments or two parts and we placed because we 3D printed them. We printed them such that we could firmly attach the two boards and these two segments of interest such that and we measured the relative orientation between these two segments in different conditions at different orientations of the same frame and we had many different frames like this.

We performed validation in terms of whether the relative orientation between the two segments were was captured relatively accurately. What we found was that only in some cases only in some designs and in some of the angles we had relatively large errors these are not very large errors about three and a half degrees. Remember this is static error and this was not there in all the cases here I am only discussing the highest possible errors.

The highest errors we found in some designs and in sum of the angles not in all the cases. So, this is how we performed the static validation.

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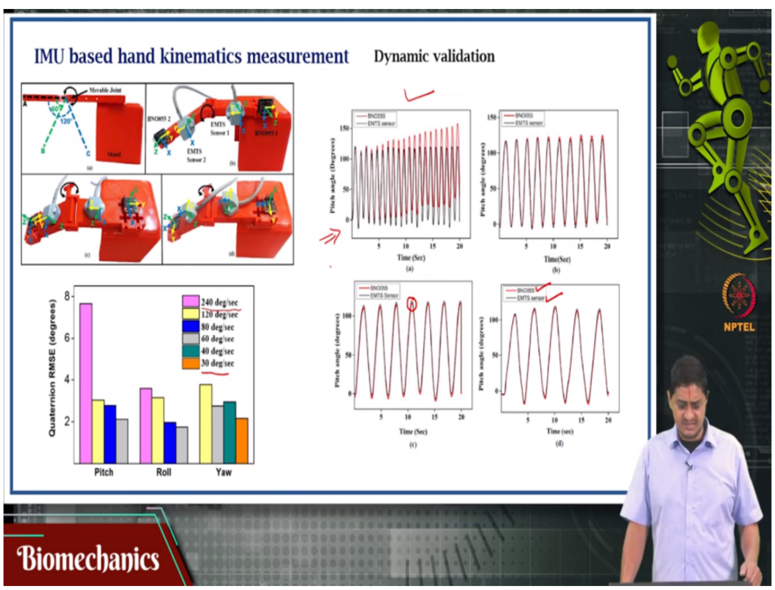

To perform the dynamic validation, we made again with 3D printed another system that could house, these PCB’s this **(()) (18:28)** PCB’s and our electromagnetic tracking sensors that are from polymers. These are polymers liberty electromagnetic tracking sensors, of course these are sensitive to metals around them and it gives us a different principle. Remember we discussed how this works in one of the previous videos.

These are sensitive to metals but the whole assembly is not made out of metal. This whole assembly is made out of probably out of PLA or ABS, this is 3D printer. So, we made it in such a way that we could rotate one of these joints at some at any speed that we want at some reasonable speeds that we want without breaking it and we oriented two of these sensors in two different joints.

So, we had electromagnetic tracking sensor and the IMU on the same platform in one segment in the other segment again we had the electromagnetic tracking sensor and the IMU. We all we assumed that the electromagnetic trackers these polymers liberty trackers will give us the gold standard joint angles. So, that is what is considered as the basis for comparison and we had a metronome that we followed that we used to rotate the joint at various speeds.

So, we rotated at various speeds starting 30 degree per second to 240 degrees per second and what did we find? Well, what is plotted here is the angles that we measured using both Bosch BNO055 and the electromagnetic tracker. Both of these are plotted and what we find is that at relatively slow speeds that is very little or no error very small amounts of error, at least it is not visible in the you are not able to identify it using your eyes but you can see if you look closely there is a small amount of error.

Especially at times when there is a directional change suddenly when there is an acceleration, suddenly when you are changing directions it seems like that is a small error that happens at relatively slow speeds. What happens at the highest speed is what caught our attention that is presented in this frame. What happens at the highest speed is once you start moving at this highest speed the Bosch BNO055 starts showing some error.

And it turns out that this error appears to propagate from one cycle to the other. In other words, as the number of cycles increases the error appears to become bigger and bigger and bigger. Remember this is a cyclical task we just did tick tick tick tick tick tick tick, so it is a cyclical task. If you do a cyclical task at a very high speed you are going to have a relatively large error towards the later cycles especially towards the later cycles in your Bosch BNO055 a measurement this is what we found.

Then we asked the question does it really matter how often are you going to perform the same cyclical task at very high speeds how likely it is in human movements we thought and we still believe that that is a not a very likely scenario. So, this is not something that we need to worry about because here we are interested in measuring relative orientation between segments in everyday life.

And in everyday life you rarely perform these high-speed moments for very long time in cyclical fashion that is very unlikely something that we learned. But something to keep in mind that there are these errors that happen with Bosch BNO055, where the error keeps on increasing with later cycles as a number of cycles increases the error appears to propagate that is something that we can keep in mind.

So, this is what we found and the RMS error for most cases was below 4 degrees. This is presented in one of the two papers that we just discussed the details are all available in the papers. Here I am not providing the details I am just introducing this.

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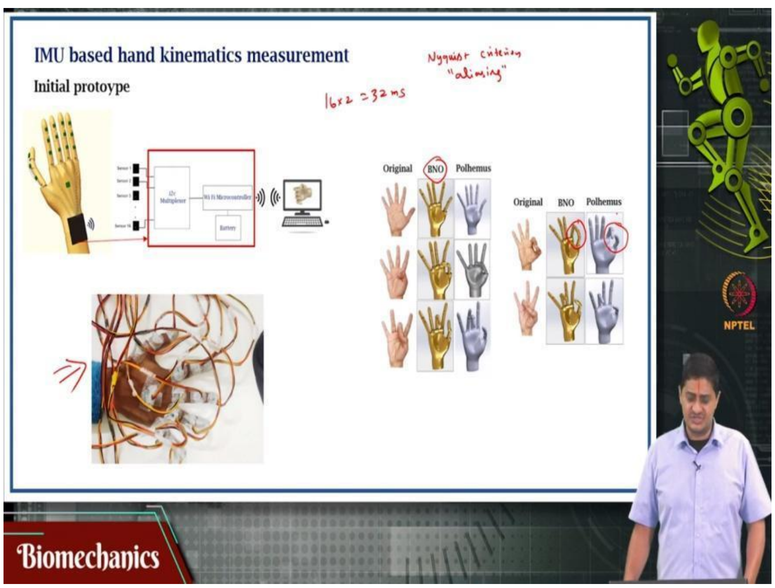

And how did we measure this we had 16 sensors remember what are these 16 sensors three sensors for each finger and five fingers is 15 and the wrist sensor of course not all of them are the same the 15th sensor. For example, is the carpometacarpal sensor which is a three degree of freedom sensor but these are 16 sensors and because each sensor has only two addressable spaces or two addressable units.

We need to find a way to measure multiple data from these many sensors. So, we used an i2c multiplexer and because each sensor takes about 2 milliseconds to provide data. Why does it take 2 milliseconds? Because it collects the data and then very quickly performs the sensor fusion and then outputs the quotient it needs that processing time two milliseconds it takes so when requested the IMU will provide data in 2 milliseconds.

And because we are using multiplexing it will the multiplexer will measure data sequentially one after the other and there are 16 of these to measure one set of angles or to measure one set of quaternions from all the 16 sensors it takes 16 times 2 32 milliseconds. It takes about 32 milliseconds to have one full set of quaternions from all the fingers from all the segments. But that means that means if I am what is the maximum speed at which I can measure?

Well, that is about 30 Hertz, if the movements are below 15 Hertz, then you will not have the aliasing problem read about this, read about what is the aliasing problem and what is the Nyquist criterion. I am just mentioning this for you to check, Nyquist criterion, aliasing problem. If the movements are going to happen at frequencies below 15 Hertz you would not have problem with measuring at 30 Hertz but you know I am a tough task master I told the students 30 Hertz not acceptable 100 Hertz minimum.

I am a task master and my students are also brilliant. They figured out a way to measure this at 100 Hertz we provide the details of how we did this in the paper but very briefly I will describe what we did, what we did was we used one microcontroller for one finger measurement. Like this we used four microcontrollers for four fingers and a fifth microcontroller that measures from the fifth finger as well as gives commands to the other four microcontrollers.

This of course increases the cost of the system but in it also increases the maximum frequency at which I can measure. You cannot have the cake and eat it too I cannot say I want to minimize the cost at the same time I want 500 Hertz measurement that is not possible you just cough up the money this is how it works you just give the money. So, I suggested at that time first let us crack the technology problem then we will crack the cost problem.

You need to add you need to decide which is the problem that you want to crack. For me this limitation of 30 Hertz was unacceptable, 30 Hertz unacceptable. It is fine, I am happy I am glad that we are able to measure 30 Hertz but I want 100 Hertz that is it no compromise see when you put some brilliant people in a situation where you know there is no compromise then they will figure out a way.

Of course, I said that there is no constraint on money there is no constraint on cost you need to give them some Levy otherwise how will they solve problems, otherwise it is impossible to solve problems you cannot put checks on all the dimensions I said that is money instrumentation hardware is not a problem but I want 100 Hertz. You need to start there and then you need to reduce the amount of hardware try to minimize it and then reduce the cost there are other ways of doing this.

But technological requirement or a technical requirement like 100 Hertz is something that I cannot compromise on. Suppose there are components of movements that is about say 20 Hertz and I know for a fact from previous experience, I have worked in this field for a long time. I know from my previous experience there are movements that have components at around 20 to 25 Hertz, some moments have not all moments these are very fast moments of course.

There are some hand finger moments that happen just about 20 Hertz, these moments will not be captured using a 30 Hertz system because of the aliasing problem. Check what these problems are because that is going slightly outside our discussion but do read up on this. So, there are constraints, the students came up with the solution thereby we use a master and slave arrangement where one microcontroller gives command to four microcontrollers that acts as the slaves.

And those four measure as soon as they receive a command from the master and measure data from one finger at a time. So, the exact solution and the details are available in the paper but briefly this is what we did. There is an increase in cost because you know five microcontrollers this **(()) (30:11)** microcontrollers that we used are expensive. Five microcontrollers means you know 5x the cost you cannot have the cake and eat it to you need to decide what you want.

So, here we focus on cracking the technical problem, in future we are still working on improving this. In future we are very confident that we will be able to develop a system that will be able to accomplish exactly this but at a fraction of the cost but that takes time. So, you need to decide which problem you want to crack first, always this is my suggestion I am not saying this is the best suggestion.

Always crack the technical problem first then crack the affordability problem these are two independent dimensions you can crack both simultaneously. First crack the technical problem so you have a grasp of the problem itself. Then the affordability cost problem can be addressed in many ways there are many ways of addressing the cost problems scale for example is one solution but not just that there are other ways of solving this.

So, that is what we did and look at the amount of cabling that we had this is this picture presents the cables that we used in the initial prototype that we had. The amount of cabling and the amount of surgical tape that we used practically people can they even move normally that is the question that is how much surgical tape and cabling that we had but that is not the point. The point is are you able to measure here we are providing proof for a principle.

This is proof of concept. We are showing that this is possible first and then we show that we then improve on this design to further make it more sleek, more unique, more special and smaller etcetera. Of course, validation of this using polymers liberty or the electromagnetic tracker and the boss behind simultaneously is not possible because it is nearly impossible in our opinion impossible to simultaneously mount the polymers liberty sensor and the IMU sensor on the finger segment.

We do have the small polymers liberty sensor in our lab we have the 1.8 mm dia polymers liberty sensor even that it is not so easy to instrument. Still working on that I will still try to see if it is possible to do that, we have to innovate. So, here we made these measurements at two different times and we show how these are rendered or represented by the Bosch BNO055 system with 16 census and polymers.

And we found relatively good accuracy with the Bosch BNO055. Remember the polymers liberty system is extremely expensive it is very expensive and also it is somewhat delicate it is fragile it will be very cautious how you use; it is very expensive. So, but the IMU system is relatively less expensive it is much less expensive when compared with the polymers liberty system and it is giving you comparable accuracy.

In fact, in some cases for example this one, the rendering in Boston was much better when compared with polymers liberty these are some examples that we show. But the point is that we are able to relatively accurately capture the finger segmental joint angles using the Bosch BNO055 IMU system.

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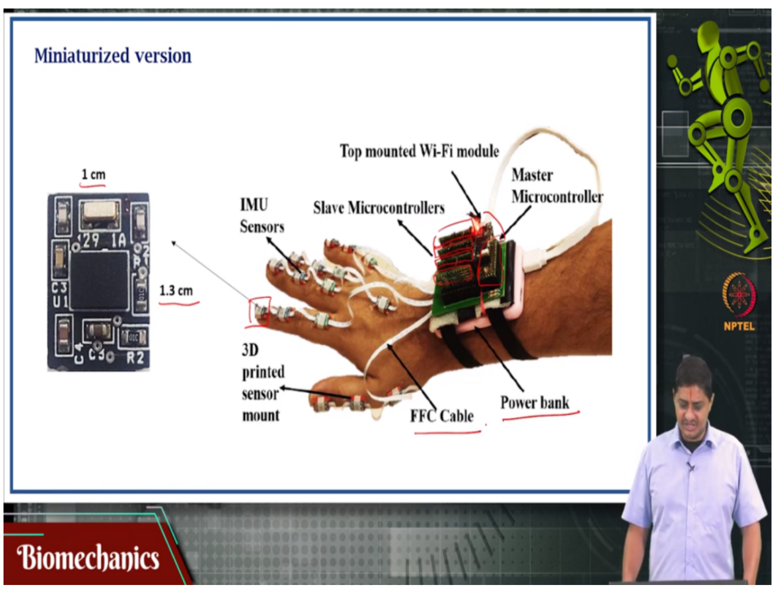

So, how did we build this; what is the final product or miniaturized version look like. So, each board it has a dimension of 1.3 centimetres by 1 centimetre and that is what is placed in one finger segment. And each of this sensor is mounted on a 3D printed mount which is then attached to the segment. Now there are many problems I know that serious followers of biomechanics will question, hey now there are many problems.

There is artefact that is a relative movement between the skin and the mount and there may be relative movement between the mount and the sensor. Yes, we have minimized the amount of movement between the mount and the sensor already. The mount is necessary because it helps us to properly attach the sensor block itself to the segment. Otherwise, you cannot directly attach a PCB because it will make the whole system fragile and extremely sensitive.

So, we need a mounting for that and then we have these four microcontrollers these are TNC 4.0 microcontrollers and then we have the fifth microcontroller here that is the master that is also our TNC 4.0 microcontroller. And we had a Wi-Fi module that sends data wirelessly to a computer and it operates out of a battery power bank. We just got a regular power bank that is available for phones just for testing purpose.

And we use as opposed to the cabling in the previous slides we used FFC cables that make the whole system a lot more manageable and a lot more sleek. So, this is what we did the size was much more manageable so, that we can actually mount it on each individual segment.

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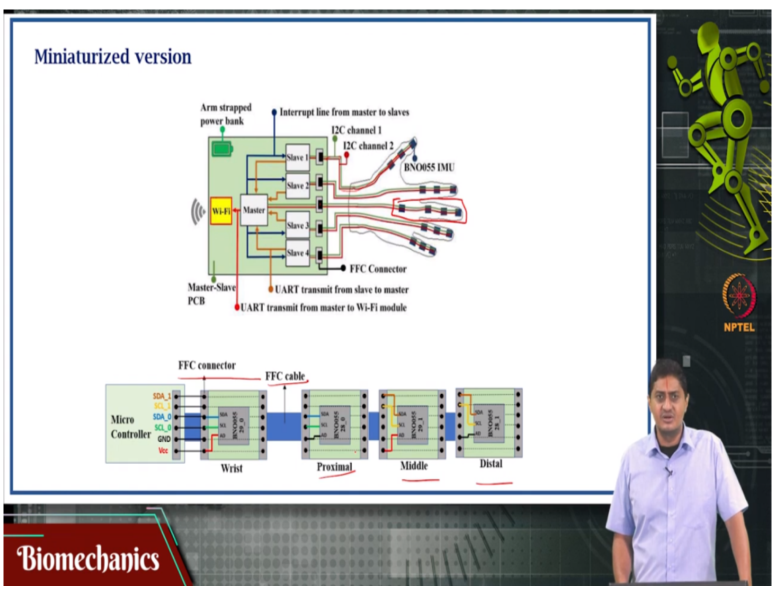

So, this is the arrangement, so you have these force layer microcontrollers sending commands to each of the fingers. This one is sending command to the it or this finger is receiving command directly from the master and it is measuring four sensor data simultaneously. So, that is the limit at which I can measure 4 times 2 milliseconds is 8 milliseconds and that means that in one second, I can measure 1000 by 8 times maximum speed at which I can measure is the maximum speed is 125 Hertz.

Of course, we are measuring only at 100 Hertz but just giving a pointer as to what is the bottleneck? The bottleneck is the one that is measuring with four sensors. Why do you need this, why do you need four sensors? Well, because I have three sets of sensors in each finger but I also have a reference sensor that is the fourth sensor in one case. So, I have five sets of three sensors and then I have one extra reference sensor.

Someone has to measure that that is measured by this master. So, this is the cable connection diagrams that provides all the little details all present in our paper, I am requesting you to please read these details in our original publications.

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Here I what is shown is rendering of measurement made using this system, real time rendering of various postures of the hand. Wi-Fi 100 Hertz real time maximum dynamic error is about 4 degrees maximum error is about 4 degrees and this is comparison between our hand kinematics measurement system and the electromagnetic trackers that we got of course not measured at the same time at two different times.

So, same task is performed by these two systems at two different times and we are just playing these animations one after the other. So, we are just playing this animation side by side I mean.

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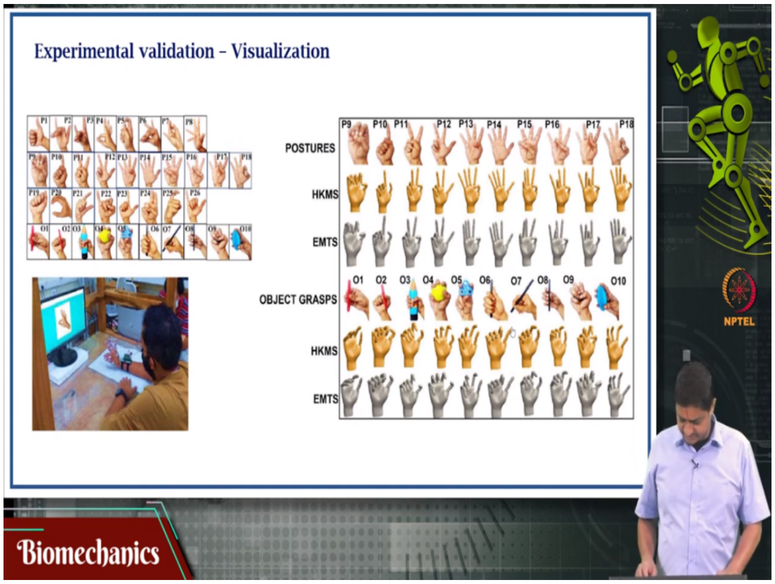

And then we used this system to try and visualize how different postures are performed by the human hand, by making people perform different types of postures. First, we started with Bharatanatyam postures because in Bharatanatyam abhinayas or finger postures are used to communicate specific feelings or emotions or whatever that is I am not an expert in that field. What is Bharatanatyam? Bharatanatyam is an Indian aesthetic dance form.

So, these are aesthetic moments, not all these postures are easy to perform some of them are hard some of them are relatively easy to perform. The point is that we captured about 10 about postures, we also used some American Sign Language postures, some numbers, some letters and we had some physical objects that was made out of plastic. Some of them used pinch grip, some of them used cylindrical grip, some of them used tripod graphs, some of them used prismatic precision grasp different types of graphs.

Using all this we made measurement using our IMU based system. And we rendered these using a software when we compared this rendering between our measurement system which we call as a human hand kinematic measurement system hand kinematic measurement system HKMS and the electromagnetic tracking system. Of course, done at two different times and we render this and we compare the rendering between the two.

And we did not find very different postures rendered by our system, the accuracy is almost comparable. So, with this innovation we have almost achieved about 30 40 fold reduction in cost, of course accuracy in research grade is compromised, our accuracy is about four degrees of the maximum error is about 4 degrees. So, it is not comparable to the polymers errors I understand that but for most purposes work on human motor control for example this kind of accuracy will be more or less acceptable. So, something to keep in mind.

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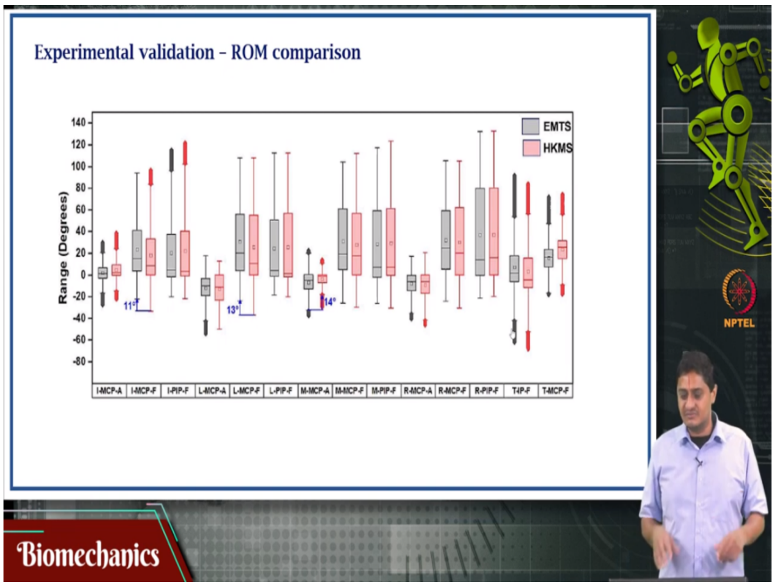

We also compared just for safety purpose just for as a check as a post check. We also compared whether the range of joint angles that you get in a set of all movements performed by a set of all participants are comparable between the electromagnetic system and our IMU-based system and we found that they are almost comparable. There were some differences in some cases and those differences are all highlighted here.

In some cases, the difference was about 14 degrees and 13 degrees and, in some cases, the HKMS had a higher range. In some cases, the electromagnetic tracking system or the EMTs had a higher range there were some differences but mostly they were comparable the ranges were comparable. The purpose of this is to show that it is not very different our system is not measuring something that is completely different physically.

It is measuring the same thing at approximately acceptable accuracy approximately comparable levels of accuracy. So, providing more confidence in your measurements.

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Here are some rendering of the various tasks that are performed. This is opening and closing of a cylinder, these are postures that are performed. Remember this all measurement is wireless 100 Hertz and because we developed it for one hand, we can instrument the one more system. On the other hand, and study two hand tasks studying two hand tasks using optical system or a polymers liberty based system is going to be extraordinarily expensive.

Very expensive even in developed countries in any lab well-funded lab studying two hand kinematics is a great challenge. And then we show rendering of movements that are performed with one hand on both hands in virtual environment. So, we see how learning is performed is what a student Anurag is doing with this free advertisement for Argulus inadvertent not meant to be an advertisement.

And then rendering of various postures for various postures how is the hand responding. This whole thing is going to cost about the cost of building it is about say 2000 dollars a one lakh rupees, a little more than that maybe. The cost at which we sell will may be different depending on this, the cost of this is about a couple of thousands of dollars very inexpensive system. Wireless 100 Hertz measurement and having an accuracy of less than four degrees.

You cannot get better than this is definitely free advertisement for our own lab product. Something that you notice with these renderings is this kind of finger touches are relatively hard to capture. Some of these finger touches are not captured especially this one where the little fingertip and the thumb are touching because this palm arch is relatively hard to model. And this so I am not saying this is a perfect system there are challenges.

But these challenges are there in all the systems these challenges palm arch is hard to model even in other systems are hard to capture even in other systems. So, capturing this little finger tip to the thumb tip is not a trivial test so we are also not able to capture. So, we are honest about that we accept what we can and we cannot do.

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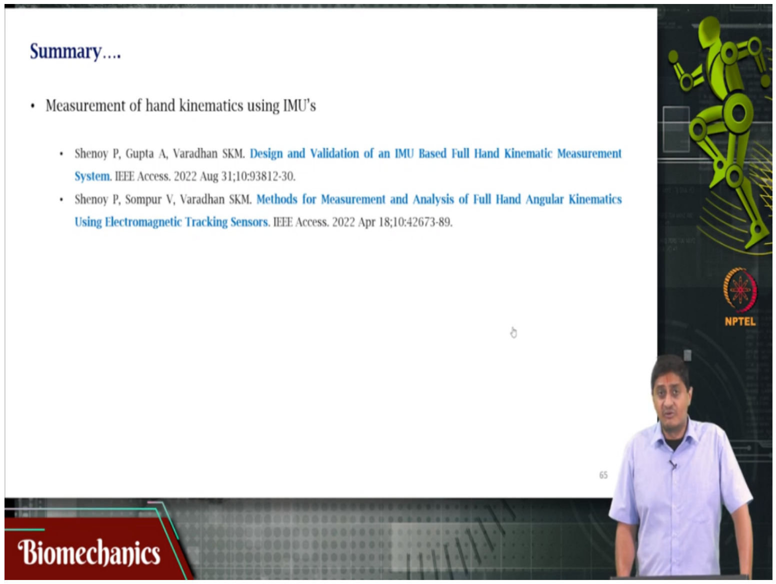

So, with this we come to the end of this video. In this video we looked at a couple of papers that is published from our lab where we used an electromagnetic tracking system to validate the performance of our in-house developed hand kinematic measurement system using IMU's and we showed that we are having acceptable accuracy levels or the errors are less than four degrees and relatively high-speed measurements captured wirelessly this and we also showed how we developed the printer circuit board for this system.

And how we measured the data using microcontroller and how we rendered it how we communicated this how we developed a communication system wireless for this system. With this we come to the end of this video, thank you very much for your attention.