

Micro Robotics

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Lecture 34

Micro Sensors and Micro Transducers - Module 09

We are discussing the microsensors and microtransducers. We have already discussed the gyroscope accelerometers, the mechanical switches, the MEMS-based switches in detail, and the flow transducers. Now we'll discuss the haptic interface and the sensor skin for the robotic system. These haptic sensors detect touch, force, and vibration while also providing tactile feedback, such as vibrations or forces, to simulate the sense of touch. The haptic interface provides a continuous sensation that allows humans to interact with computer systems and other types of machines through the sense of touch, enabling person-machine communication. It's a kind of man-machine interface that can be specifically established using this haptic interface.

Unlike a traditional interface, it provides visual and auditory information. The haptic interface generates mechanical signals that simulate the human kinesthetic and tactile channels. The haptic interface can be used to add the sensation of touch to virtual and augmented reality experiences. Ideally, the haptic system should be capable of interfacing with the processor, the driver, the actuator, and the vibration sensor. Let us see some real-life examples of these haptic devices, such as smartphones and tablets. The haptic feedback in touchscreens, such as Apple Haptic Touch and Android Vibration Alerts, is one of the examples of haptics. With reference to smartwatches and wearables, vibrations for notifications and fitness tracking feedback are examples. With reference to the laptop and keyboard, this haptic-enabled trackpad is used effectively. From the perspective of gaming controllers, force feedback is used in the PlayStation Dual Sense and Xbox controllers.

From the perspective of haptic VR gloves, they allow users to feel virtual objects; for example, these are haptic gloves. Now, with reference to robotic surgery and telemedicine, a da Vinci surgical system provides force feedback to surgeons to appropriately incorporate

the system into their procedures. As far as the haptic steering wheel arrangement is concerned, A vibration alerting drivers to lane departures is one of the practical applications of these haptic steering wheel-based systems. Touchscreen controls, which have haptic feedback in infotainment systems, provide a safer driving experience. Haptic pedals and seats provide vibrations in the seats for safety warnings.

A remote operation of robots with haptic feedback enhances the control of robotic arms in hazardous environments. Aerospace flight simulators, a force-feedback tool in pilot training, are some examples of these real-life applications of haptics. In order to closely understand the haptic system, one needs to have exposure to the components of the haptic interface, such as sensors. It detects the user's input and interaction with the environment and also measures the force exerted by the user on the interface. With reference to the actuator's perspective, it generates physical feedback, such as forces, vibrations, or movements.

With reference to the control system perspective, it processes information from the sensors. It manages feedback generation through the actuator and implements an algorithm to create a realistic haptic sensation. From a software perspective, a mathematical model of a haptic feedback algorithm for synchronizing haptic and visual feedback is needed. As far as electronic components go, it has a control sensor, actuators, and a processing signal to manage the power. The sensor used for the haptic interface is important; the haptic interface uses various types of sensors to detect user input and interaction, which includes force and pressure sensors, i.e., a piezoresistive sensor, a piezoelectric sensor, a capacitive sensor, and a triboelectric sensor. These sensors detect contact conditions, pressure values, and force distribution when users interact with the haptic interface. With reference to the temperature sensor's perspective, there is a pyroelectric sensor. These pyroelectric sensors are used to detect temperature changes and provide thermal feedback. The tactile sensor perspective, a sensor mimicking human mechanoreceptors like Merkel cells, Ruffini corpuscles, Meissner corpuscles, and Pacinian corpuscles, is one of the human mechanoreceptors or corpuscles that is being established.

These sensors detect various tactile stimuli, such as pressure and vibration, in these textures. Let us discuss the actuators used in a haptic interface. These actuators are used in various combinations depending on the specific requirements of the haptic interface, such as precision, power consumption, form factor, and desired tactile effects. Let us take an example of an eccentric rotating mass motor. It consists of a balanced weight attached to a motor shaft.

The rotation creates a kind of vibration, and it is commonly used in mobile devices. This is a type of rotating motor with an eccentric mass and a linear resonant actuator; it uses a magnetic mass that is attached to a spring. It produces a more precise and controllable

vibration and is often used in high-end smartphones and controllers. So, from the perspective of a linear resonant actuator, it has a spring, a mass, a magnet, and a coil assembly. A mass with a spring and a magnet that is available here is mainly meant for proper deflection studies. These actuators are used in haptic interfaces, such as piezoelectric actuators, which use materials that deform when an electrical current is applied. It provides high-frequency and localized feedback; it is also used in advanced touchscreens as well as precision-related applications. With reference to the perspective of electroactive polymers, these materials change their shape or size when stimulated by an electric field. It can create more complex and textured sensations and is more about developing a kind of commercial application. The feedback in a haptic interface can offer more interactive means, mimicking the feeling that an event occurs naturally to enhance the effects of virtual reality and thereby advance the user experience.

The haptic feedback in human-machine interaction (HMI) now includes vibrations and electrical feedback, which can not only transmit contextual information but also provide people with clear, accurate, and less intrusive information. This feedback and haptic interface are concerned with providing a form of kinesthetic feedback. These kinesthetic feedbacks are nothing but simulations of weight, pressure, and force through the muscles, tendons, and joints. It is used in force feedback devices like joysticks and VR controllers; it also provides a sense of resistance and movement. The tactile feedback simulates the sense of touch on the skin's surface and includes several subtypes, such as vibrotactile feedback.

These vibrotactile devices use vibrations to simulate textures and provide alerts. As far as electrotactile stimulation is concerned, it uses electrical impulses to stimulate the nerve endings in the skin. As far as ultrasonic tactile technology is concerned, it creates a mid-air tactile sensation using focused ultrasound waves and thermal feedback that simulates a kind of temperature change. The force feedback applies forces to resist or assist user movement. It is used in gaming controllers and virtual reality systems and enhances realism by simulating physical interactions.

The textured feedback provides detailed information about the surface properties and can be achieved through spatial tactile feedback or vibrotactile patterns. The electromagnetic feedback uses a magnetic field to create a kind of tactile sensation. It is less common but is used in specialized applications like haptic feedback suits; thus, it is more on the wearable side. Let us discuss the kinesthetic feedback in the haptic interface. This kinesthetic feedback provides users with a sense of movement, position, and force through the muscles, tendons, and joints.

To simulate this physical property of the object, it ideally needs to have different parameters, such as size, density, and resistance. For example, in the case of a video game character, a character who uses a heavy vehicle might require more force to move, providing a realistic sense of weight and resistance. With reference to the micro-robotic perspective, there are various types of kinetic feedback-based haptic interfaces used to control the movements of micro drones. These drones can move within a particular domain, and the orientation of the drones can be changed through this haptic interface. To classify this kinesthetic feedback, it is divided into two categories: one is called passive kinesthesia, and the other is called active kinesthesia. So, this type of feedback only impedes the user movement by providing resistance. It is based on the physical attributes of objects, such as texture, weight, and rigidity. So this kind of passive kinesthetic feedback is commonly used in robotic surgery, where surgeons sense the resistance and pressure during the operation, enhancing precision and realism. In the case of active kinesthetic feedback, it can both impede and assist the user's movements. It actively applies force to guide or support the user's action, simulating the interaction with the virtual object.

Some examples can be found in VR gloves, haptic exoskeletons, and specialized gaming devices. It enhances immersion and realism by simulating the physical properties of objects in the environment. The tactile feedback refers to the physical sensations experienced when interacting with a surface or device that provides information. Some key aspects include texture, vibration, and pressure. Tactile feedback includes both spatial and nonspatial types. A spatial type has surface friction, skin indentation, and electrostimulation. Like in these particular cases, it offers more detailed information about the edges, shapes, and contact; spatial haptics utilizes mechanical technologies such as friction, surfaces, and skin indentation deformation. The electrical simulations stimulate nerve endings to trick the user's brain into feeling contact. The non-spatial vibration provides a sense of texture and cues through vibrational patterns. Now, let us talk about the control system in the haptic interface.

There are two popular control methods that are widely used in haptic controller designs. One is called impedance control, in which the operator's motion input is measured and the reaction force is fed back to the operator. Next is called "admission control." In admission control, the force exerted by the operator is measured, and the positions are fed back to the operator. Both impedance and admittance control are basic methods for interacting with virtual environments. It might be either a human-machine interaction or a human-robot interaction. Let us discuss the sensory skin for robotic systems. The sensory skin is a recent advancement in soft robotics that has led to the development of a skin-inspired sensory system that closely mimics the functions of human skin and muscle. These innovative robots integrated electronic skin, called e-skin, with artificial muscles. It enables them to sense and adapt to their environment in real time.

The sensing capabilities of eSkin include a pressure sensor that detects the normal forces applied to its surface. A strain that measures the deformation and stretching, a shear that senses the lateral force and friction, temperature that monitors thermal changes, and humidity that detects moisture levels in the systems. As far as UV is concerned, it measures ultraviolet radiation exposure. From a proximity perspective, it detects nearby objects without any contact. From a vibrational perspective, it senses high-frequency mechanical oscillations in these systems. The overall sensing mechanism utilizes various transduction methods to convert physical stimuli into measurable electrical signals. This measurable electrical signal can take the form of a resistive type. It might be in the form of a capacitive type, a piezoelectric type, or a triboelectric type. It can be in the form of a thermal type or an iontronic type, which are kinds of high-resolution slip sensing employed. In robotic sensing, there is vision sensing; some of the components of vision sensing include lighting, lenses, image sensors, vision processing, communication, and data collection.

From a functional perspective, it allows the robot to perceive its environment and gather information about it. With reference to the sensor's point of view, it has both an orthographic projection and a perspective projection. From an application perspective, it focuses on the navigation and localization of the system. The robotic sensing and hearing senses are also considered to be two of the key parameters for robotics. In this particular case, it has microphones, other sound sensors, and amplifiers in place. It also has the analog-to-digital converters that participate in this particular robotic sensing system. A computer system, algorithm and software and a data collection will also participate in this. As far as functionality is concerned, it perceives sounds in its environment and gathers information about them. As far as sensor types are concerned, it has a sound sensor, a piezoelectric sensor, an ultrasonic sensor, and infrared sensors, which are all different types of sensors used. From an application perspective, it has sound localization and tracking capabilities.

Sound classification and noise cancellation are considered to be among the applications. Now, with reference to robotic sensing, we have the tactile sense, where sensing, data collection, data processing, decision-making, and actuation play vital roles. With reference to the sensing, it has perceived physical contact and gathered information. There are different types of sensors, including pressure sensors, temperature sensors, force sensors, strain sensors, and tactile sensor arrays, which are considered some of the robotic sensing systems. The key applications are concerned; they include object identification, force feedback, and surface sensing, all of which contribute to tactile sensing. Now we can also consider the electrical nodes. Some components of sensing include the sensors, the data acquisition system, the data analysis system, a sample introduction system, a power supply, and housing. It detects and identifies different chemical compounds. Some of the sensors include the metal oxide semiconductor sensor, the quartz crystal microbalance sensor, and the surface acoustic wave sensor. A gas sensor includes a solid-state gas sensor, an infrared

gas sensor, a catalytic gas sensor, and an electrochemical gas sensor; some nanowire gas sensors are also used in this electronic nose.

Then, we have the mass spectrometry sensor, which also contributes. Now, with reference to the application perspective, we have the chemical analysis, odor tracking, and environmental monitoring, which exhibit results. Now let us talk about the electronic tag, which is used as a type of robotic sensor. So, in the case of an electronic tongue, there is a wide variety of groups that work on conductive polymers, ion-selective electrodes, optical fibers, surface acoustic wave devices, and data collection. The main functionality includes detecting and identifying; it is mainly meant for detecting and identifying different chemical compounds. Some of the key aspects include the pH sensor, the conductivity sensor, the temperature sensor, the chromatography sensor, the electrochemical sensor, and the spectroscopic sensor. From an application perspective, it is used for chemical analysis and flavor detection. From a systems perspective, it has sensors, manipulators, processors, and a power supply. It has housing with an enclosure, a communication system, a machine learning system, and a data collection system. This allows the robot to perceive its environment and interact with it in various ways. There are different types of sensors available. One is a kind of temperature sensor, pressure sensor, humidity sensor, and camera that also contribute to the overall processing of the systems. The microphones and the LIDAR sensors also get integrated for this excellence. With reference to the overall perspective, it involves viewing, mapping, and creating a multimedia reading experience. It is for making calls and interacting with physical objects. This is a kind of tactile sensor in the first robot, which has a tactile LED back and an LED head sensor.

This is located on the robotic head, and this sensor is likely designed to detect touch or proximity. It can be used for a kind of interaction and allows the robot to respond with a physical contact gesture. There is a stereo microphone there, which is positioned near the head area; the stereo microphone enables the robot to capture sound in high fidelity. These features likely support the voice recognition and the audio command or environmental surround sound reductions. With reference to face detection, there is an aluminum-faced LED panel. This panel appears to serve as a display on the robot's face. It might be used to express emotions, provide visual feedback, and communicate information through dynamic LED patterns. A distance sensor is deployed at the front of the robot. This sensor helps measure the distance to objects or obstacles. It is likely used for navigation, collision avoidance, or spatial awareness.

And there is a tactile LED back sensor situated on the back of the robot. This tactile sensor detects touch inputs on its rear side. It might support the interactive features or provide feedback when touched. There is a pause button sensor, a physical button located on the body of the robot, possibly used to pause its operation or put it in standby mode. These are some types of commercially available sensors that are being developed for different applications related to tactile and other monitoring systems.

Now, let us discuss a new concept called machine skin. In machine skin, a customized smart material-based flexible sensor can be integrated into any kind of legacy structure. This is mainly meant for a macro-level system. However, by using a certain number of flexible triboelectric generators, they can also be integrated into a simple micro-level system. Let me just give you a simple example. Since there is a lathe, it needs to be condition monitored. This is a pretty old lathe, and instead of considering this particular lathe, some of the key parameters involved are the temperature sensors and the temperature generated by spindle rotation. A vibration due to the undulation in the structure, a flow due to the movement of the liquid, and a kind of strain that is established are present here. Now, all these sensors should be at the micron level, and they should be on a customized base system. A kind of customized structure can be deployed by integrating smart materials or by designing smart materials to sense these particular parameters. For example, in the case of a temperature sensor, it can utilize a customized shape-memory alloy structure. A vibration sensor can use a customized triboelectric nanogenerator. Microstrain measurements can use SMA-based strain gauges. A flow measurement can use optical fiber-based sensors. A pseudo-elastic SMA for vibration damping, etc.

Now, whichever sensor data is being connected can be used. These systems can be modeled in the form of a digital twin so that all the sensory data can be captured and monitored through it. This digital team will continuously interact with the machine and try to capture the data that can be used for prognostic-related applications. The concept of machine skin has been proposed to address the issues. It consists of an array of IoT-enabled sensors strategically positioned on the surface of a machine to collect data on numerous parameters, such as temperature, variation, flow rate, and strength. So the collected data will subsequently be processed and analyzed for prognostic purposes, and the results will be displayed on the dashboard via a server-based system.

This resulted in the creation of a digital twin depicting the entire machine and allowing the operator to visualize and understand the prognostic data in a user-friendly way. Some of the key advantages of this machine skin process are that, like any kind of legacy machine or any machine that requires customized sensing, such machine skins can be deployed. The second important advantage on which the machine skin is focused is that it is a kind of self-energizing system that doesn't require external power. The third important point is that the energy generated by these triboelectric nanogenerators can be efficiently used to power the IoT module so that it acts as a plug-and-play module, and from this plug-and-play module, the digital tools will start working and interacting. So this machine's skin is completely new, and it has been taken up to the next level for different applications.

Next, this is a type of case study. So in this case study, it is a kind of gesture-based, SMA-actuated robotic hand for human-machine interaction. Currently, we are discussing more about Industry 4.0-related applications. However, there is a need to move towards the

Industry 5.0 application, which is more focused on the human-machine interfaces. The man-machine interface is concerned; the sensory system that has been deployed should be capable of interacting with the main system so that it can be used for seamless communication, and then a kind of seamless transformation can occur. There is a need for a gesture recognition system, and this system should be capable of appropriately interacting with the microcontrollers, relays, SMA robotic hand, and power sources. Now, the main motto of this particular process is that it is a glove integrated with a flux sensor used for gesture recognition. However, on the other hand, there is a kind of 3D-printed hand with SMA-based robotic structures and SMA-based actuators. When these gesture gloves are appropriately moved, the robotic hands also get actuated, and a relay circuit is deployed that controls the position and orientation of this SMA-based robotic hand.

This is a kind of demonstration and training that is being deployed for gesture control. The glove, which is integrated with the flux sensor and gesture recognition, involves a type of control signal in which different gestures are recorded. Either it may be a one-finger movement, a two-finger movement, or a three-finger movement. Appropriately, these signals are translated to the moment. For example, this is a kind of gesture that is shown, and the distance between the man and the machine is approximately eight meters. Appropriately, when the gesture is made, the movements are translated into handling the system. This is a simple technology. The thought process behind this technology is a kind of remotely operated bomb diffusion system. This is a type of wire cutter that is placed here and is operated using a man-machine interface that employs gesture control in the robotic system. There are different kinds of high-resolution electronic skin that are also used for such applications.

One of these is robotic sensory skins. Instead of flexoelectric or shape-memory alloy structures, a type of piezoelectric sensor is being deployed. In these piezoelectric structures, a robotic sensory system with a large area and higher resolution electronic skin for robots is embedded. The research focuses on creating flexible and sensitive e-skin that can enhance robots' abilities to interact with their environment and perform complex tasks. The e-skin uses a piezoresistive sensing mechanism. The e-skin covers a large area of approximately 70 centimeters by 50 centimeters, with high-resolution sensing units totaling around 5,806 units. And the e-skin can detect pressures as low as 20 pascals and 28 pascals, so it has a fast response time of 30 milliseconds. It allows for real-time sensing, and the E-skill can be successfully integrated with the robotic arm. The main advantage of such a high-resolution electronic skin is that it can achieve real-time tactile sensing and grasping control of the robotic hand. By considering the hardness, surface roughness, and brittleness of the object to be grasped, it is also used to compare the real-time pressure distribution on the robotic hand with preset values. It decides when to stop grasping and when to lift the object, and it grasps delicate components such as paper and balloons without damaging them. In fact, it is also the case for the silk industry; these are used to

grasp it appropriately for silkworms, among other things. The system simulates the tactile and motion feedback processes of human skin, nerves, and muscles and can be directly attached to the surface of existing intelligent machinery. It offers the advantages of compactness and easy installation without requiring any major changes to the mechanical structure. These are some types of high-resolution, electronic skin-based systems that are being deployed in robotic applications. Just to summarize, the main objective of this particular module is to understand the impact of microsensors and microtransducers.

It's a kind of high level, focusing more on the acquisition and manipulation of related systems. The content comprises gyroscopic accelerometers, mechanical switches, flow transducers, a haptic interface, and sensory skin for the robotic system. We have discussed the overall classification of gyroscopes. Some of the key aspects of the gyroscope include the vibrating structures, the classification of these vibrating structure gyroscopes, including the ring gyroscope, the tuning fork gyroscope, the hemispherical resonator gyroscope, and the dynamically tuned gyroscopes. We have also discussed the optical microscope-based gyroscope accelerometers, which include a fiber optic gyroscope and a ring laser gyroscope that do not require any kind of mechanical structure.

We also had a discussion on micro-mechanical switches regarding their overall configuration and basic working principles, which include the magnetic field, the LED field, the membrane switches, and the snap action that exists. Then we had some discussions about these MEMS-based switches. In the case of MEMS-based switches, we discussed the different configurations, including electrostatic switches, electromagnetic switches, electrothermal switches, and shape memory alloy switches. Some of the key parameters involved in designing and fabricating such switches include the switching time, the transmission performance, and the contact resistance; we also discuss the reliability characteristics. The overall application of such MEMS-based switches, along with the major challenges and advantages involved, is significant.

Some of the recent advances in these switches include a micropower Hall effect switch, a multi-material-based switch, self-enhancing piezoelectric actuators, soft electromagnetic actuators, and polymer-based electromagnetic actuators. Some of the future trends that are involved include AI integration for predictive maintenance, self-healing contacts, energy harvesting applications, biodegradable switch technologies, and enhanced integration with IoT and smart systems. A brief discussion about the flow transducer, different configurations of the flow transducer, key components of the flow transducer, some of the features, the energy conversion mechanism, the measurement methods, signal processing, and the overall roles of these flow transducers and micro-robotic systems are needed. It also covers the different types of flow transducers, including thermal transfer methods.

Then the time-of-flight methods, thermal time-of-flight methods, ultrasonic methods, and a discussion of magnetic inductive principles, vortex principles, and courtesy flow sensors were covered in detail. A new concept of triboelectric nanogenerator-based flow sensors has been discussed, and the demonstration of it has been presented here. Then we had an interaction about this haptic interface, including the overall application, the components involved, the sensors used, the actuators used, and the feedback from the haptic interface. The classification of this haptic interface can be defined with reference to kinesthetic feedback, tactile feedback, and the overall control system involved in the haptic interface. We also had a discussion about this sensory skin for robotic systems. The various types of robotic sensing being established include vision, hearing, tactile sense, electronic nose, electronic tongue, and 60 other senses.

We also had a discussion about the tactile sensor for a commercially available robot and how tactile sensors are being employed. There is a concept of machine skin that is emerging in a larger way. The machine skin has potential applications in the man-machine interfaces and the man-robot interfaces. So one case study on machine skin has been demonstrated. A gesture-controlled robotic system for controlling the robot even from a remote location. This is a kind of demo that was presented to show how the gesture control works, even at an eight-meter distance, and how it is being controlled and monitored. Higher resolution electronic skin for microbots and how these higher resolution skins are employed in robotic-related applications. These are the references that have been used for this particular lecture.