NUS National University of Singapore

EE5111/EE5060 Selected Topics in Industrial Control & Instrumentation

Force Sensing

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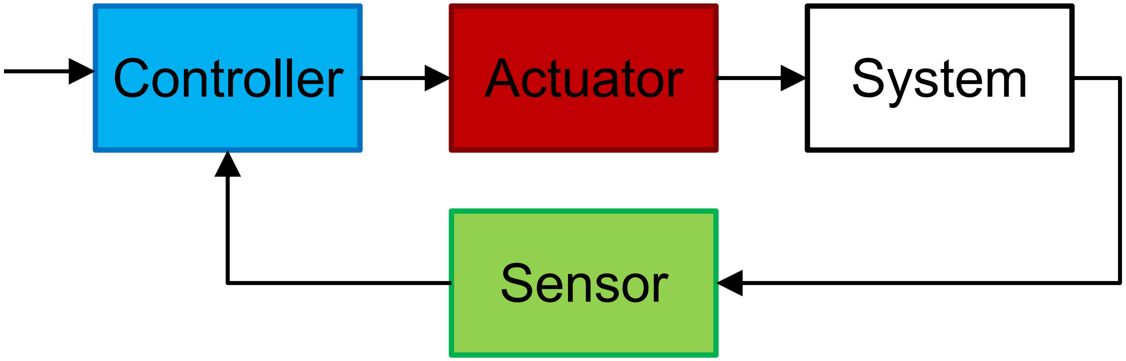
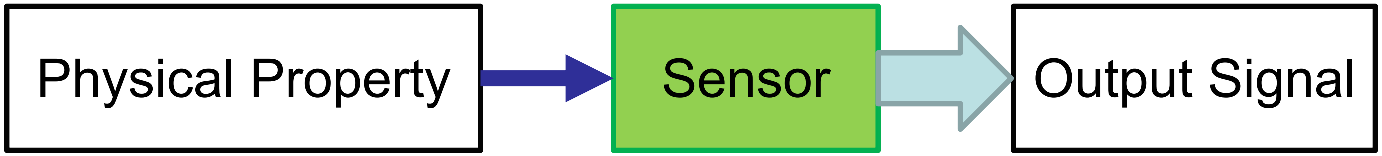
Recap

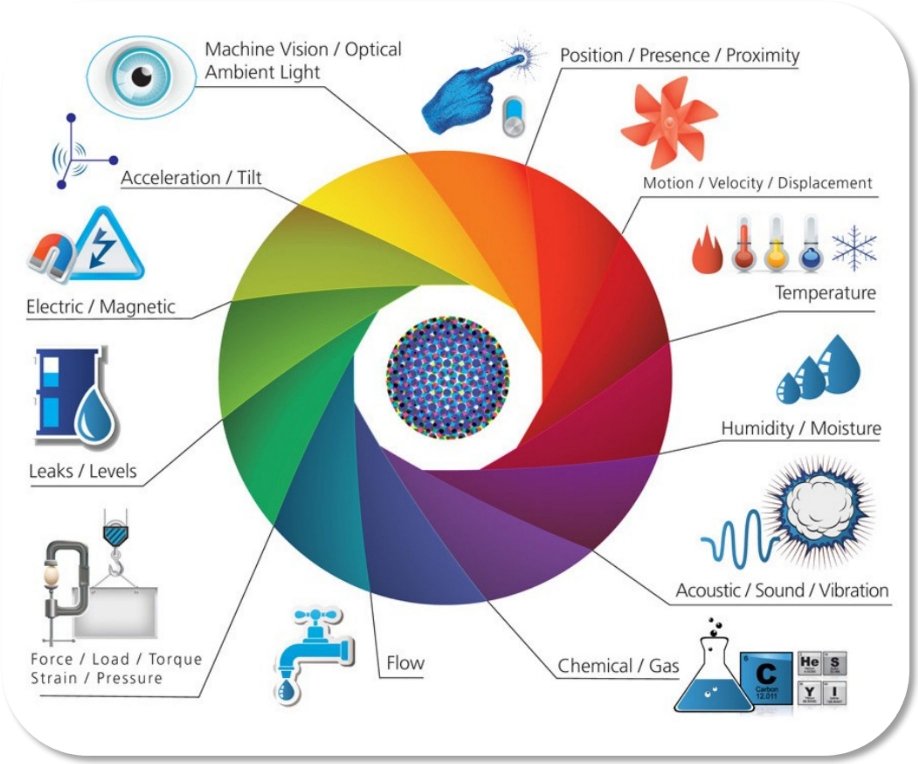
- **Feedback Control**
  - What & Why?
    - A *Feedback Control System* is a system which tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control. (*Mayr Otto, 1970*)
    - A *Modern Controller* **senses** the operation of a system, **compares** that against the desired behavior, **computes** corrective actions, and **actuates** the system to effect the desired change. (*Karl Johan Åström & Richard M. Murray, 2008*)
  - How?
    - Controller
    - Actuator
    - Sensor



Recap

- **Sensor**
  - What?
    - A device which detects or measures a physical property and records, indicates, or responds to it.
  - Types of Sensors
    - Tactile Sensors
    - Force Sensors
    - Mechanical Sensors
    - Thermal Sensors
    - Optical Sensors
    - …

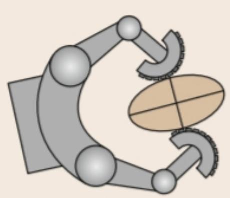




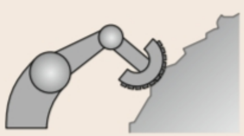
(Source: https://www.postscapes.com/)

Overview

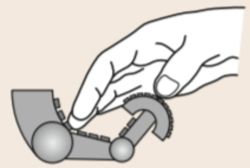
- **Force Sensing and Control**
  - What?
    - A *force* is any interaction that, when unopposed, will change the motion of an object.
    - A *sensing system* is a sensor or a set of sensors whose excitation behaviors we want to study.
    - *Force control* is essentially a kind of approach that controls the dynamic interaction between a system and its contacting object
  - Why?
    - *Maintain the contact force within an acceptable range*
    - *Control the applied force to follow a desired reference*



Manipulation: Grasp force control; contact locations and kinematics; stability assessment.



Exploration: Surface texture, friction and hardness; thermal properties; local features.



Response: Detection and reaction to contacts from external agents.

(Source: *Springer Handbook of Robotics*)

Topics to Be Covered

- **Force Sensors**
  - Basic concepts & main types of force sensors
  - Applications
- **Force Sensorless Estimation**
  - Methods
  - Applications

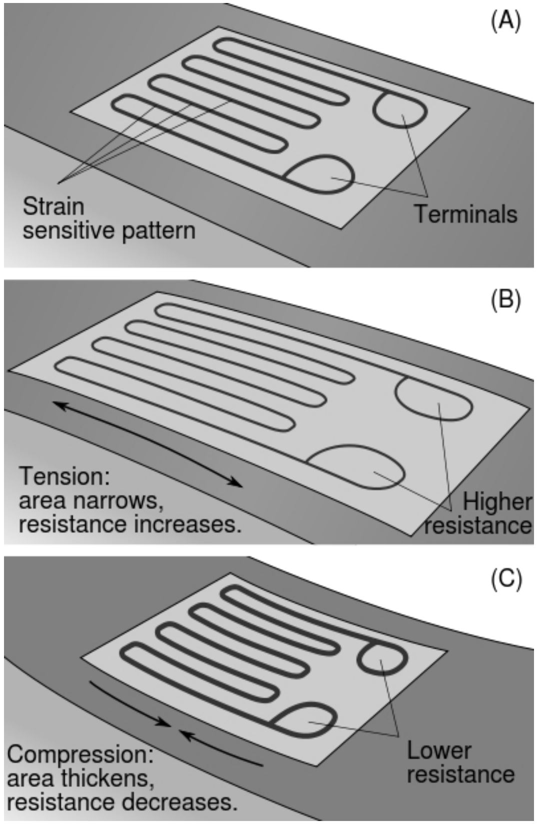
Force Sensors

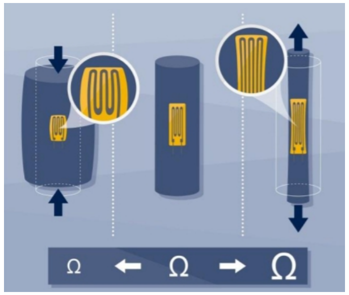
Force Sensors

- **What are Force Sensors?**
  - A device that converts an input mechanical force into an electrical output signal
- **Main Types of Force Sensors**
  - Strain Gauge (Load Cell)
  - Force Sensing Resistor (FSR)
  - Piezoelectric Force Sensor

Force Sensors

- **Strain Gauge**
  - A *strain gauge* is a device used to measure strain on an object.
- **Working Principle**
  - As the strain is proportional to the deformation that is related to the applied force, the applied force can be measured via the strain measurement
- **Gauge factor**
  - The ratio of relative change in electrical resistance to the mechanical strain



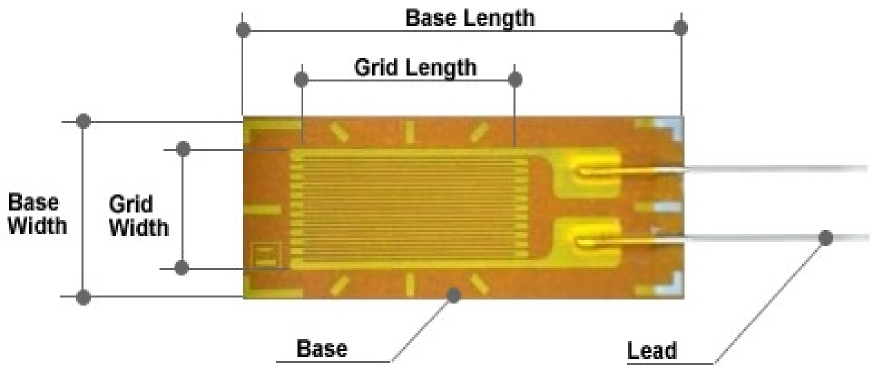


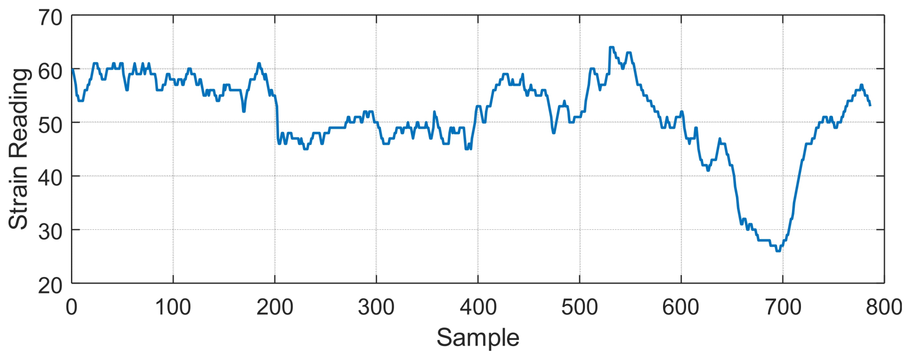
$$K_{GF} = \frac{\Delta R/R}{\varepsilon}$$

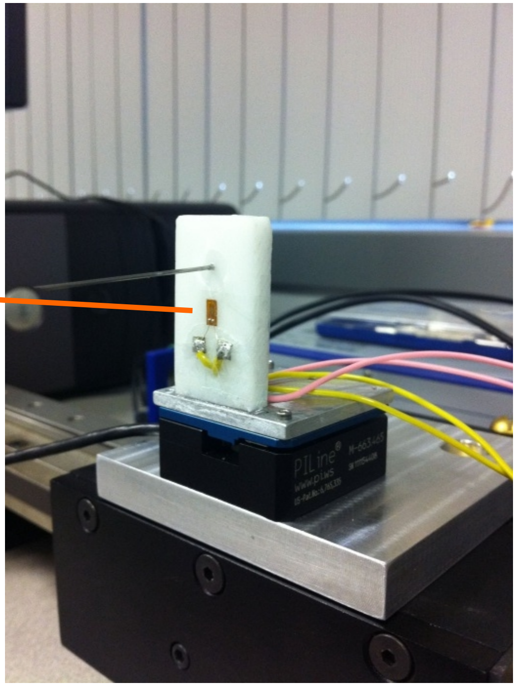
$$\varepsilon = \Delta L/L$$

Force Sensors

- **Strain Gauge**
  - Its resistance is related to the applied force
  - Work with a beam







Force Sensors

- **Wheatstone Bridge**
  - A circuit transforms resistance change to voltage change

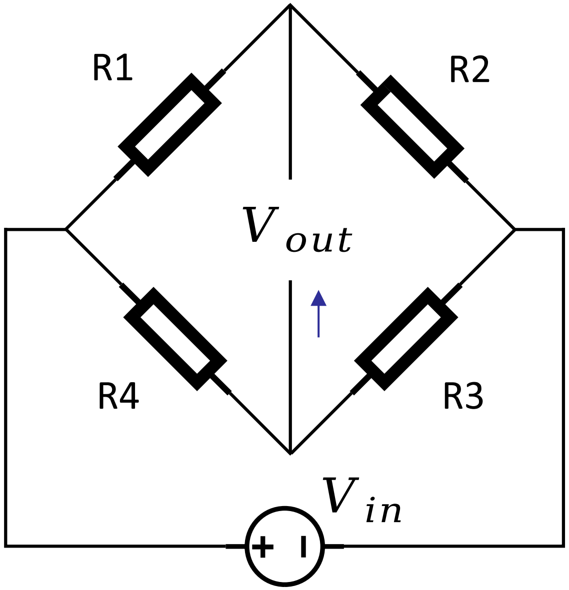
$$V_{out} = \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}\right) V_{in} = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} V_{in}$$

  - For a balance bridge, $\frac{R_1}{R_2} = \frac{R_4}{R_3}$
  - Consider the fact that

$$\frac{\Delta R_i}{R_i} \ll 1$$

  - We have

$$V_{out} \approx \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) V_{in}$$



Force Sensors

$$V_{out} \approx \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) V_{in}$$

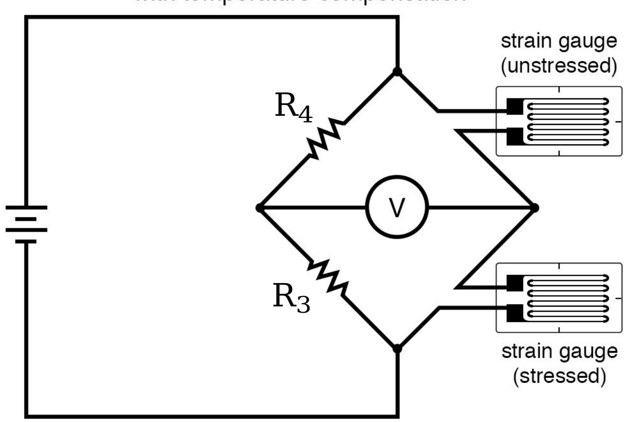
p.s. $K_{GF}\varepsilon = \Delta R/R$

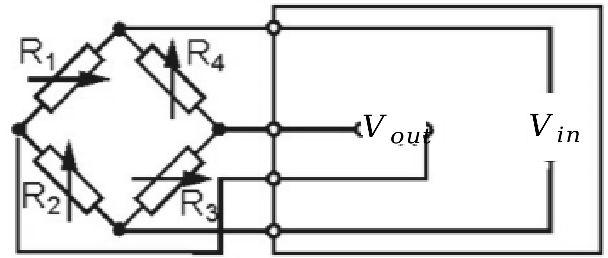
- Wheatstone Bridge
  - Different versions
    - Quarter bridge
    - Half bridge
    - Full bridge

$$V_{out} \approx K_{GF}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)V_{in}/4$$

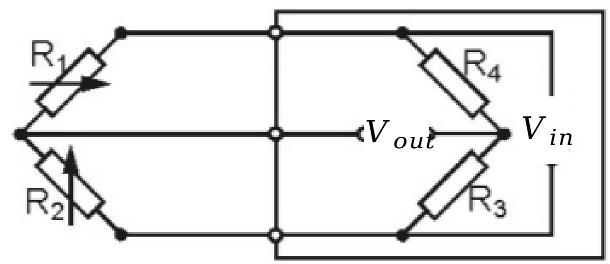
  - Temperature compensation

Quarter-bridge strain gauge circuit with temperature compensation

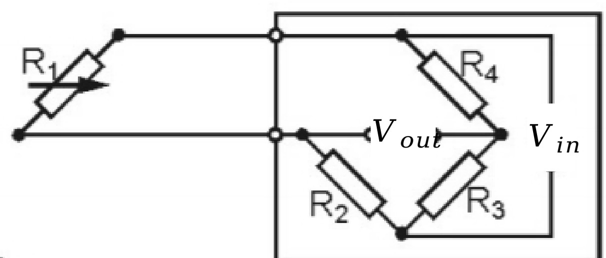




a) Full bridge



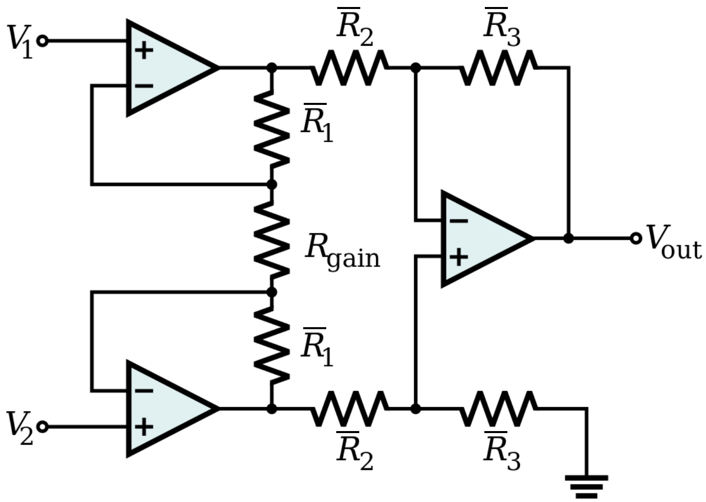
b) Half bridge



c) Quarter bridge

Force Sensors

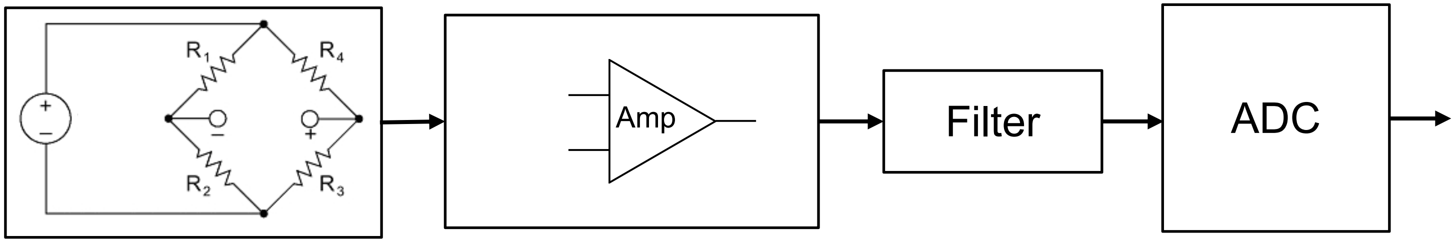
- **Instrumentation Amplifier**
  - A special type of *differential amplifier*
  - Features
    - Very low DC offset
    - Low drift
    - Low noise
    - Very high open-loop gain
    - Very high common-mode rejection ratio
    - Very high input impedances
  - Amplifier Gain
    - Adjust by only one resistor



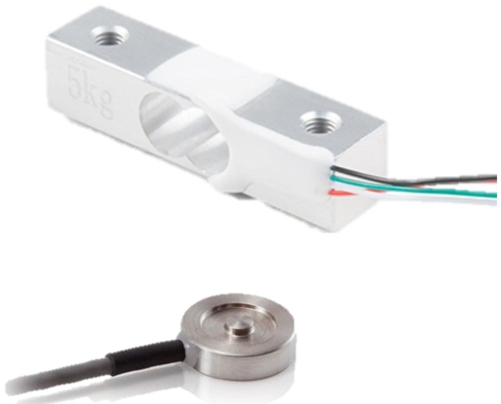
$$A_v = \frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2\overline{R}_1}{R_{gain}}\right)\frac{\overline{R}_3}{\overline{R}_2}$$

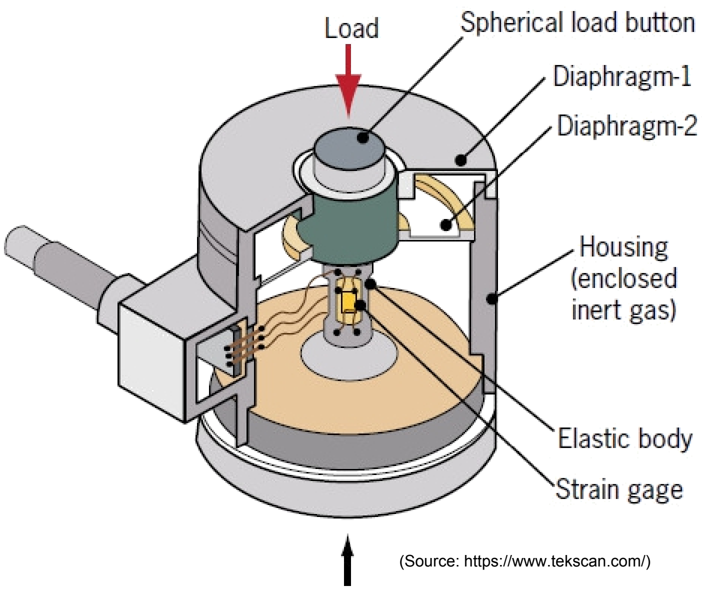
Force Sensors

- Load Cell



  - A type of force sensor that, when connected to appropriate electronics, return a signal proportional to the mechanical force applied to the system.

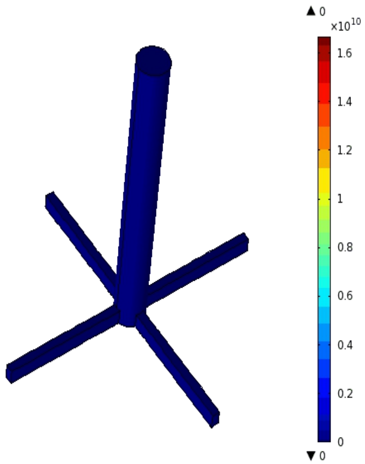


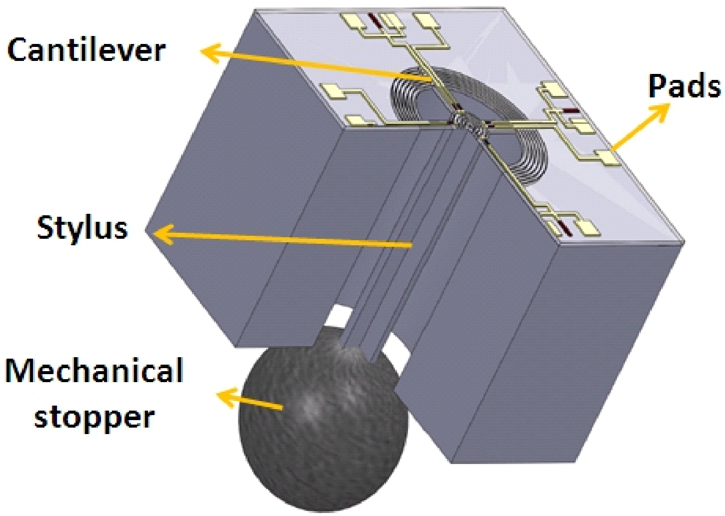


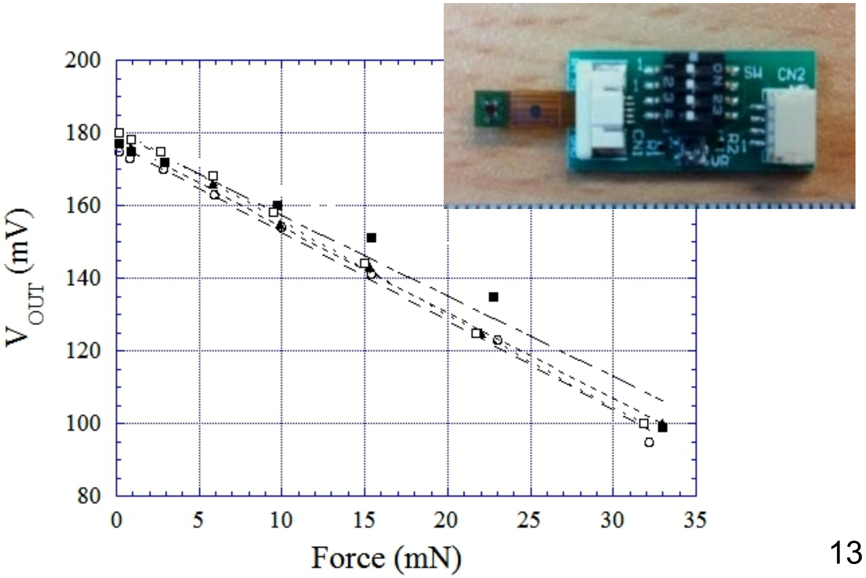
(Source: https://www.tekscan.com/)

Force Sensors

- **Piezoresistive Force Sensor**
  - Silicon Nanowire Force Sensor
    - Force → Strain → Resistance
- **Piezoresistive Effect**
  - The electrical resistance of a semiconductor or metal changes when mechanical strain is applied.

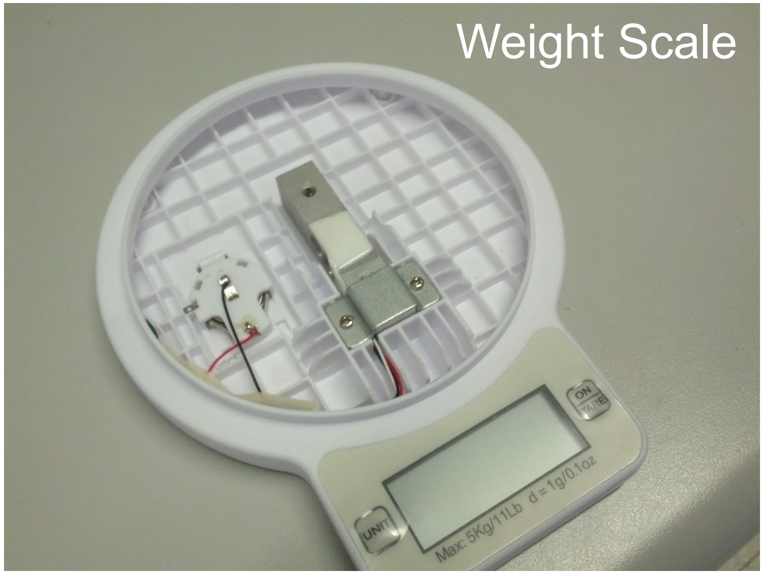


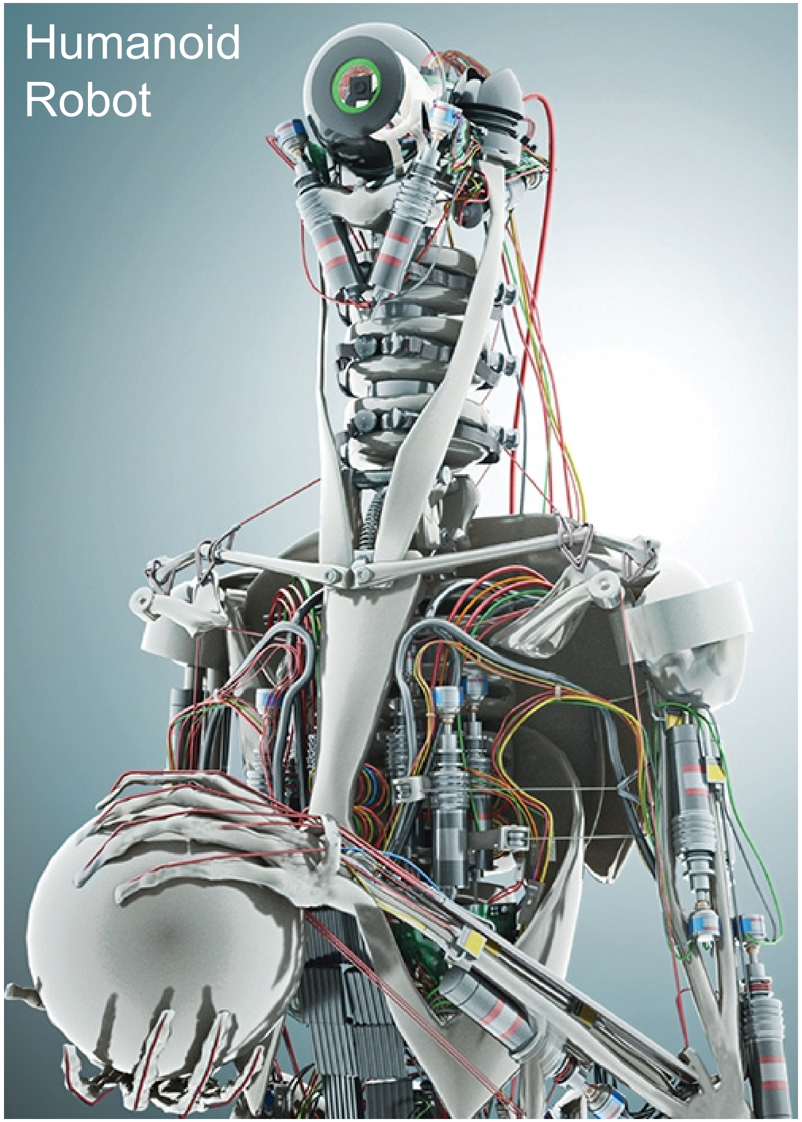




Force Sensors

- **Applications of Load Cell**
  - Widely used in many many applications

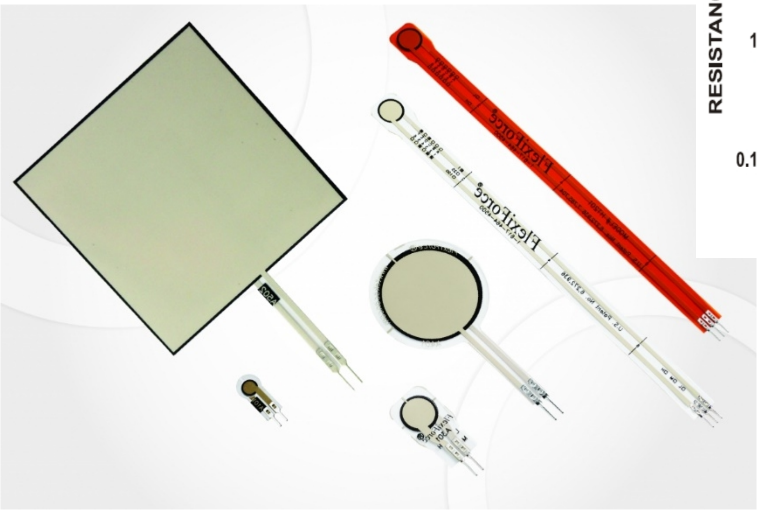


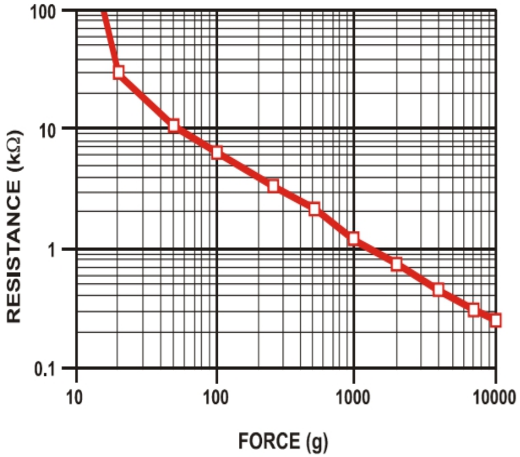


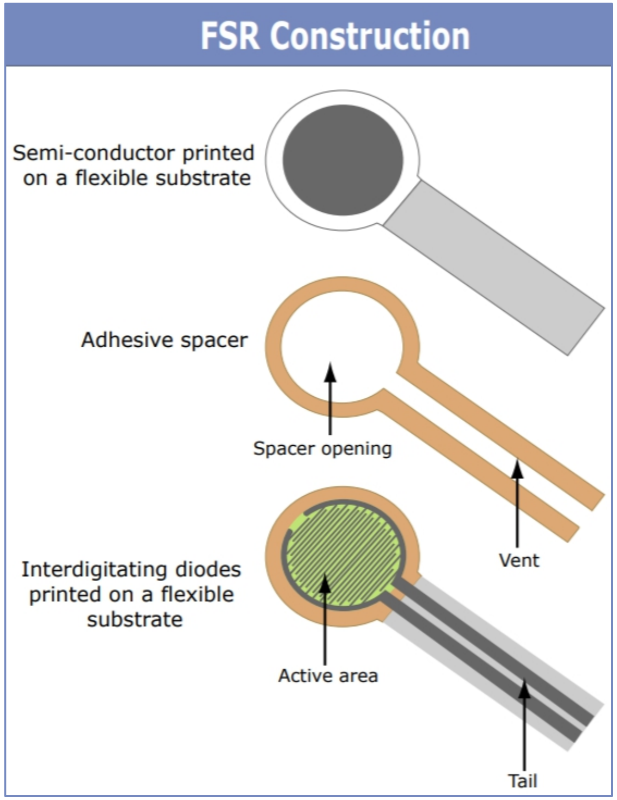
(Source: http://www.futek.com/)

Force Sensors

- **Force Sensing Resistor (FSR)**
  - A material whose resistance changes when a force, pressure or mechanical stress is applied.
  - A conductive polymer





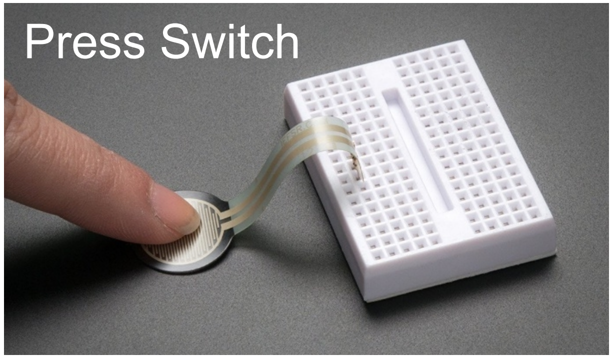


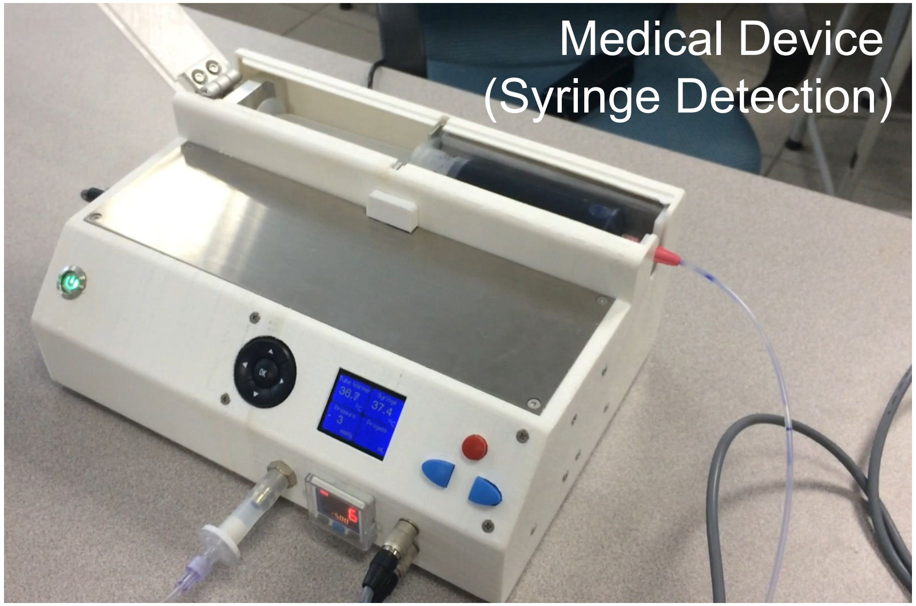
(Source: MIT OpenCourseWare)

Force Sensors

- Applications of FSR

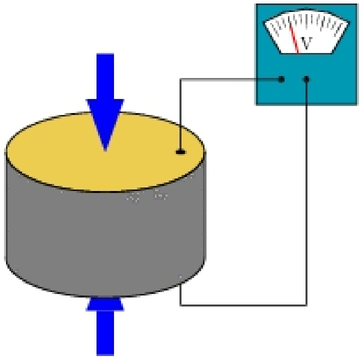
(Source: IEEE Transactions on Biomedical Engineering)

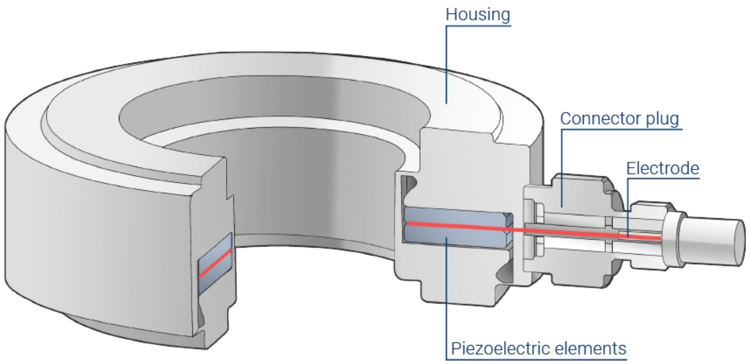




Force Sensors

- **Piezoelectric Force Sensor**
  - A *piezoelectric sensor* is a device that employs the piezoelectric effect for the measurement of pressure, acceleration, strain or force by transforming them to an electrical signal.
  - *Piezoelectric materials* are materials that produce an electric charge under mechanical stress





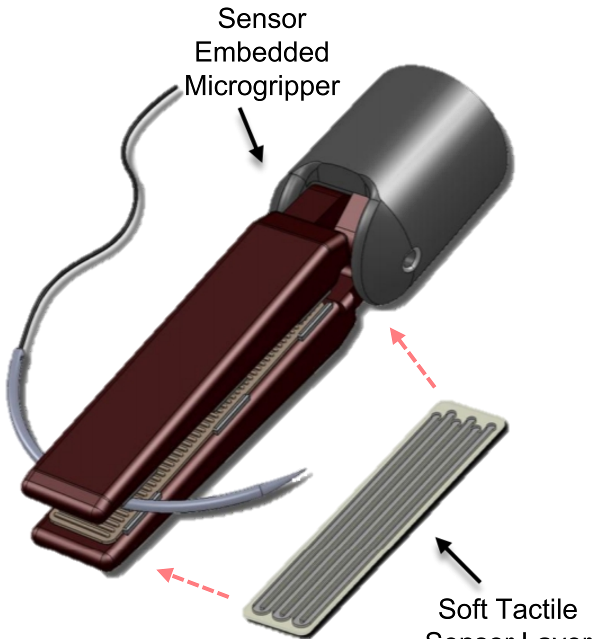
(Source: https://www.hbm.com/)

Force Sensors

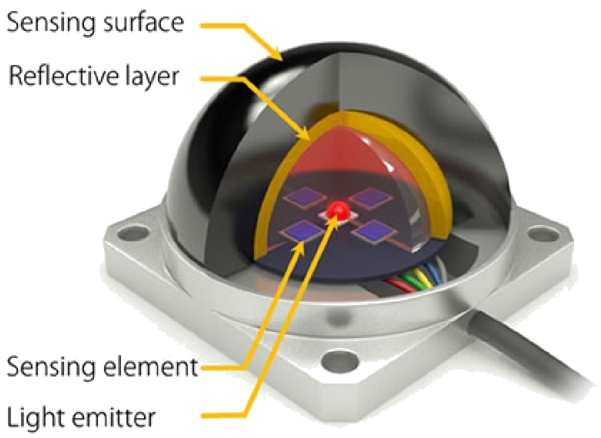
- Applications of Piezoelectric Force Sensor

Force Sensors

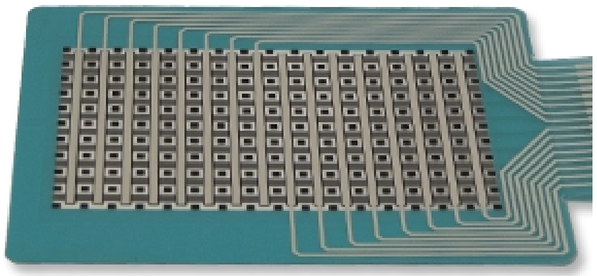
- **Other Force Sensors**
  - Tactile Sensor
  - Optical Force Sensor
  - Force Sensor Array/Network
  - …



(Source: Harvard University)



(Source: http://www.quadratec-ltd.co.uk/)

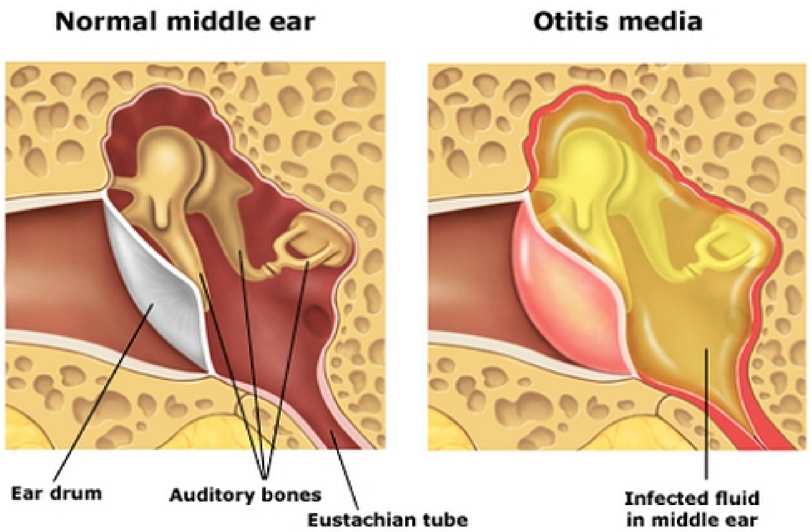


Force Sensors - Applications

Force-based Supervisory Control for Robotic Surgery

Force Sensors - Applications (Problem)

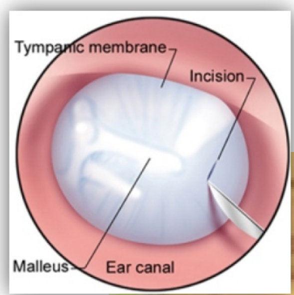
- **Otitis Media with Effusion (OME)**
  - Collection of fluid that occurs within the middle ear space
  - Very common ear disease
- **Main reason**
  - Defects in Eustachian tube due to orientation, size, allergy, genetics or after bouts of flu and cold
- **Serious Clinical Effects**
  - Hearing impairment
  - Brain infection
  - Middle ear bone erosion / Tumour
  - Speech, language & academic delay in children
  - Death arising from complications



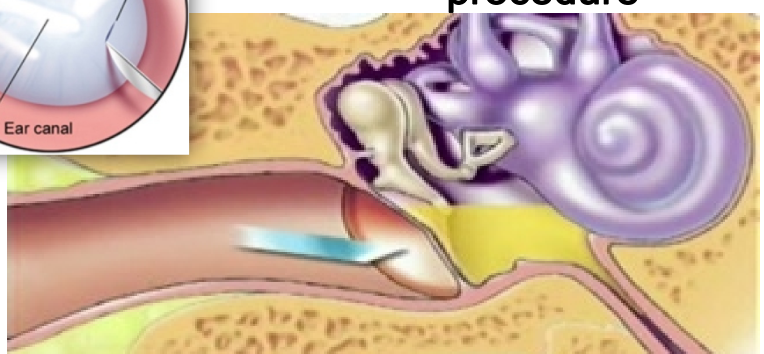
(Source: http://www.humandiagram.info/)

Force Sensors - Applications

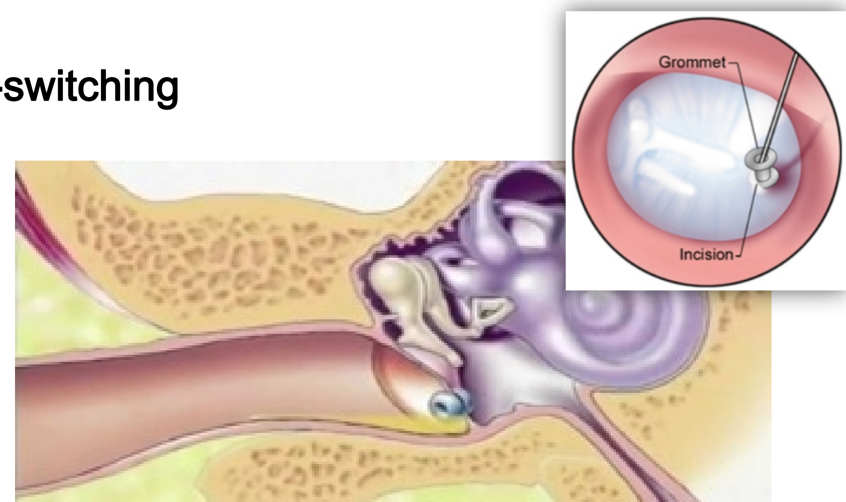
- **Current treatment of Otitis Media with Effusion (OME)**
  - Surgically insert a ventilation (grommet) tube on the eardrum
  - Patient under **General Anesthesia (GA)**
  - Two main steps
    - Myringotomy (incision making on eardrum)
    - Grommet tube insertion



Multiple steps and tool-switching procedure



Myringotomy



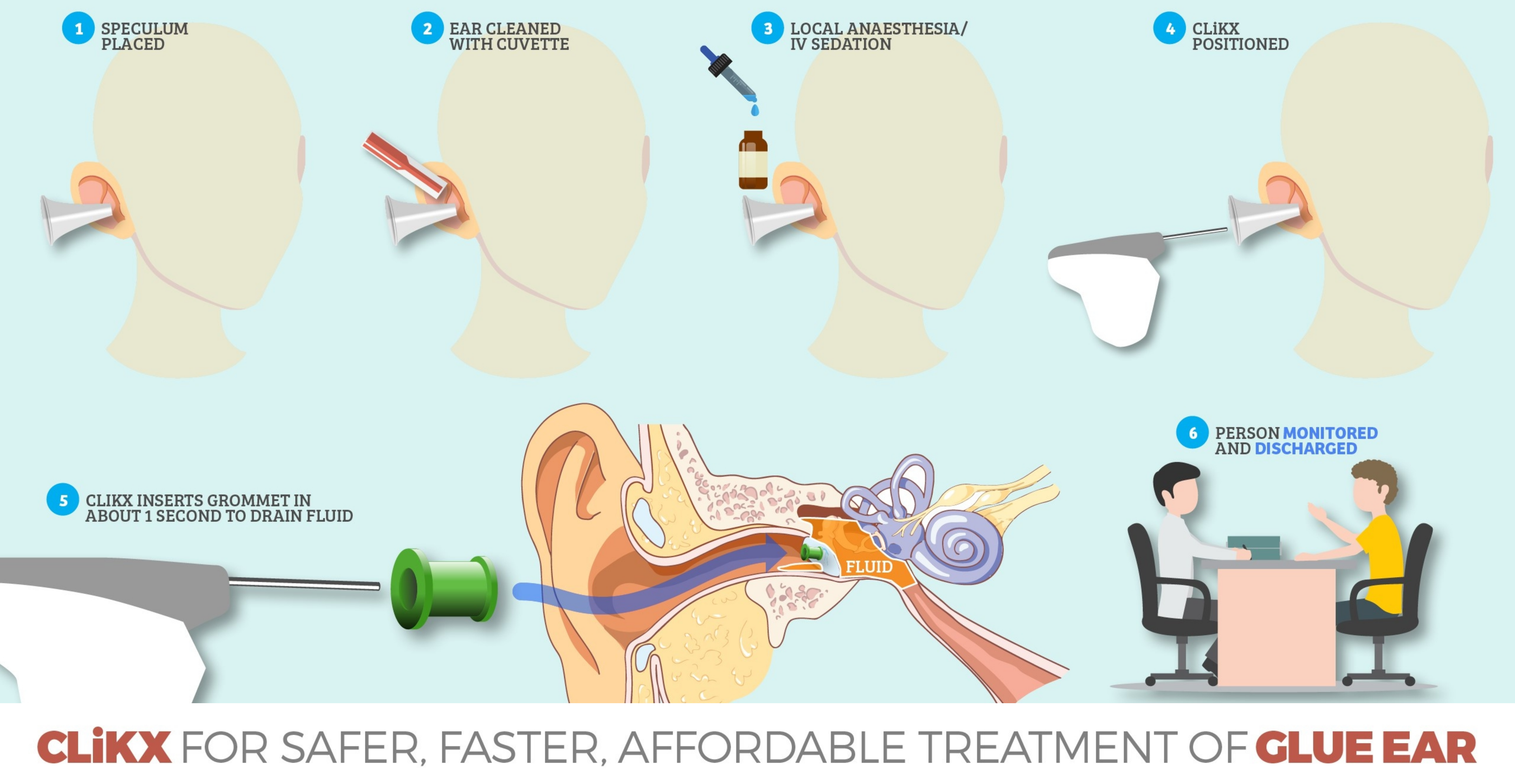
Grommet tube insertion

Force Sensors - Applications

- **Issues of Current Treatments for OME**
  - GA is associated with risks
  - Highly surgical skills
  - Costly operating theatre time and equipment
  - Reduced access for patients in underserved areas
  - Delay in treatment

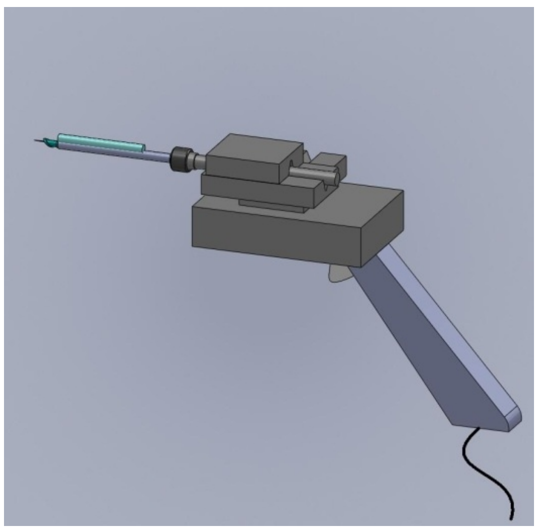
Force Sensors - Applications

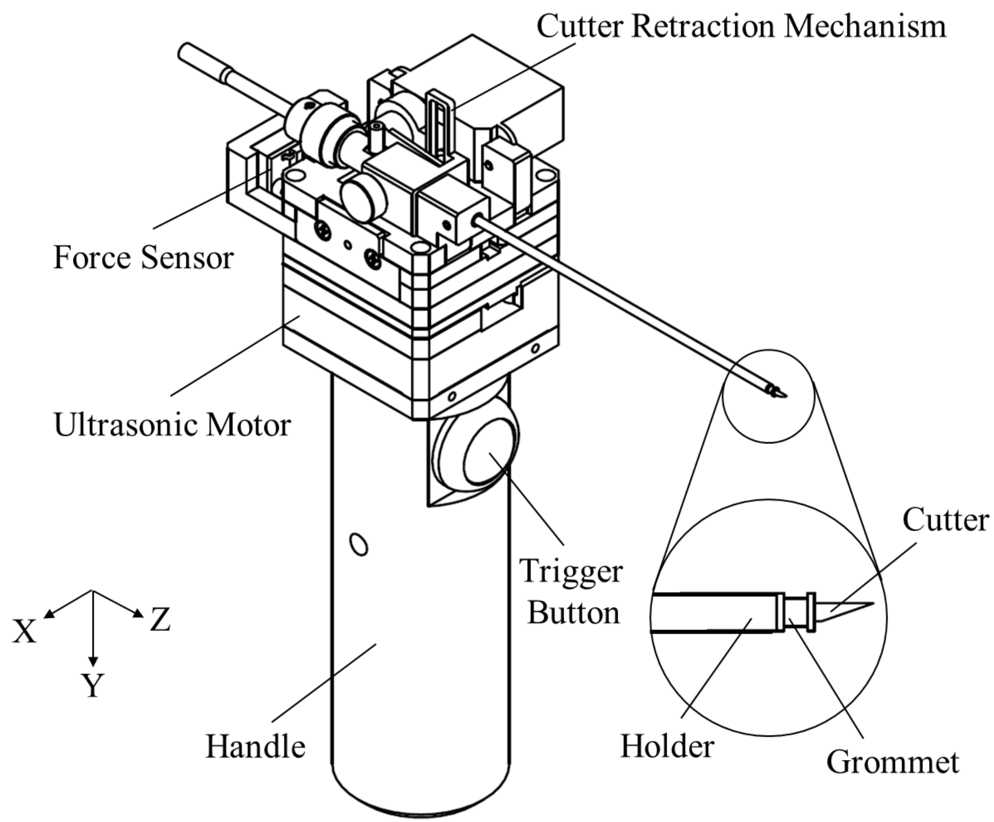
- Ventilation Tube Applicator (VTA): CLiKX



Force Sensors - Applications

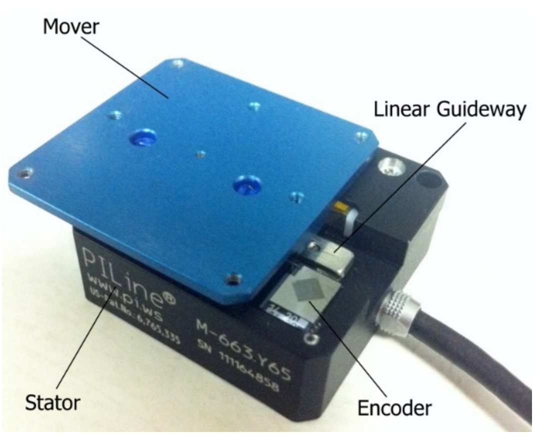
- **First of its Kind**
  - “Point-Click-Insert” tube applicator (Ventilation Tube Applicator, VTA)

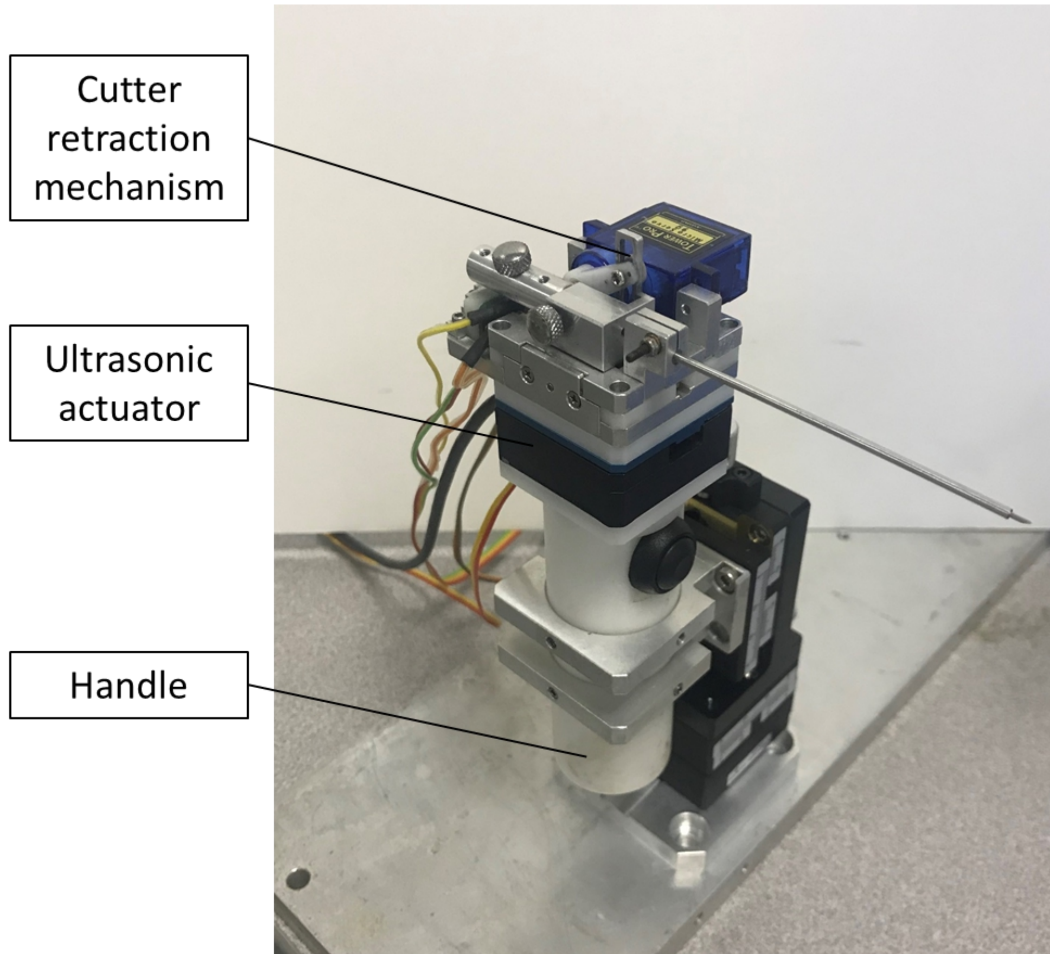




Force Sensors - Applications

- ## Mechanical System





Force Sensors - Applications

- Working Process
  - Initialize and find the desired insertion location
  - Touch detection
  - Make an incision
  - Insert the grommet
  - Fully retreat the cutter and release the grommet


(A) Touch detection

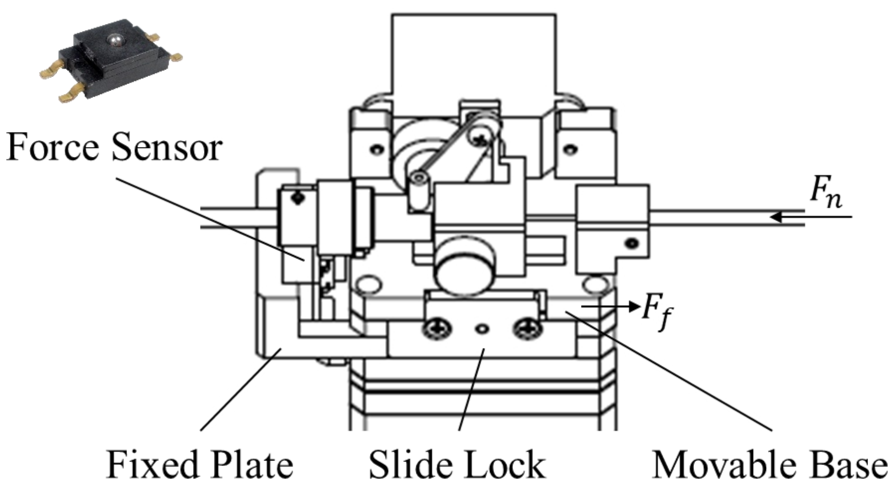

(B) Myringotomy

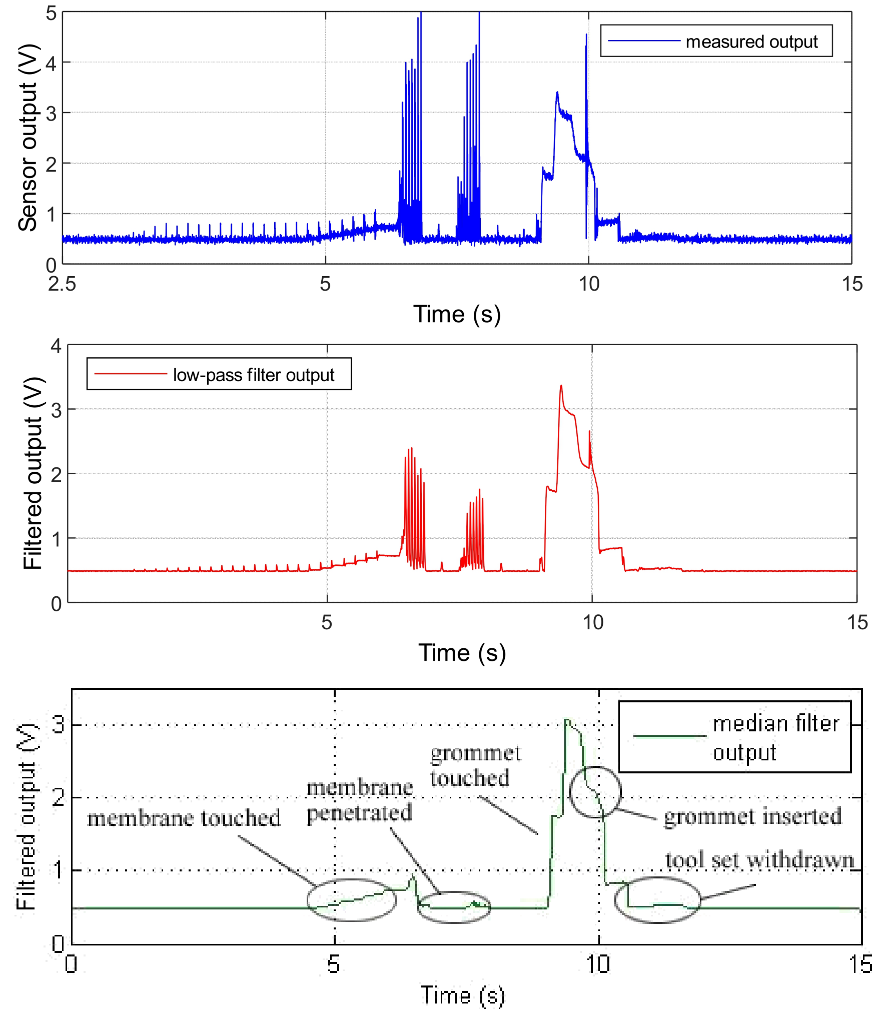

(C) Tube insertion


(D) Tube release

Force Sensors - Applications

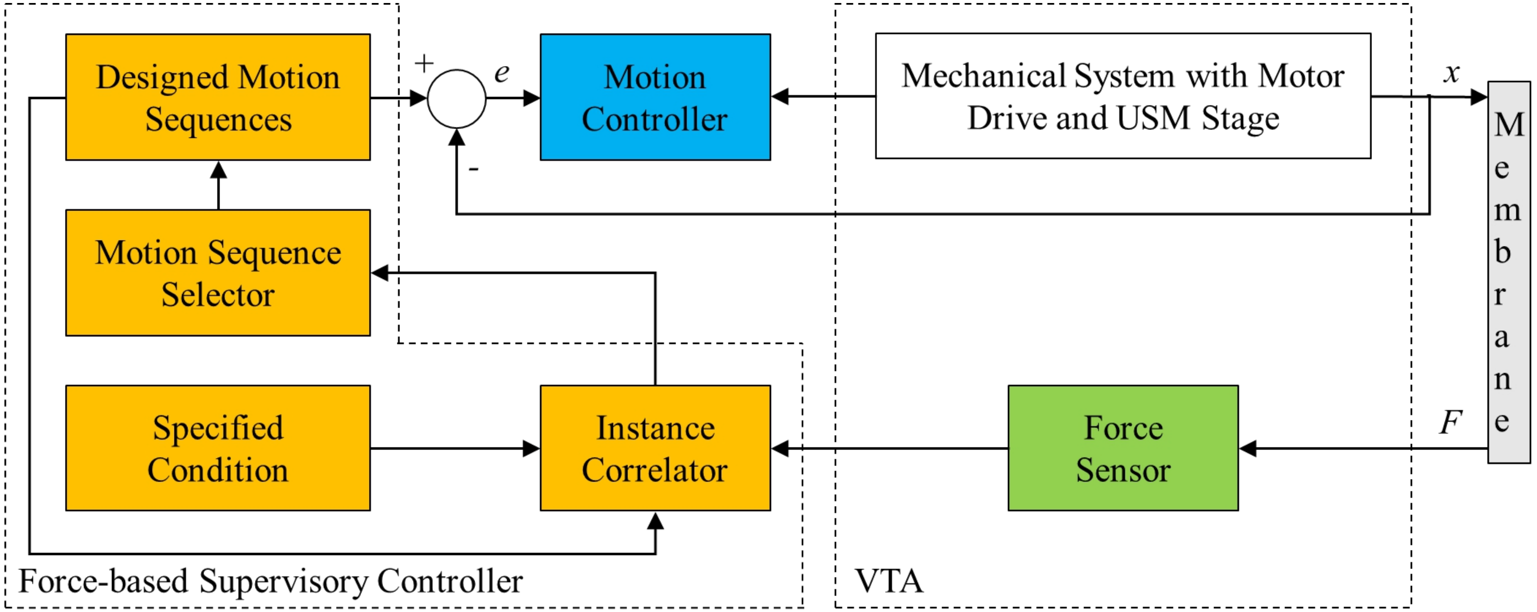
- **Force Sensing System**
  - Piezoresistive Force Sensor
  - Sensor installation
  - Median filter





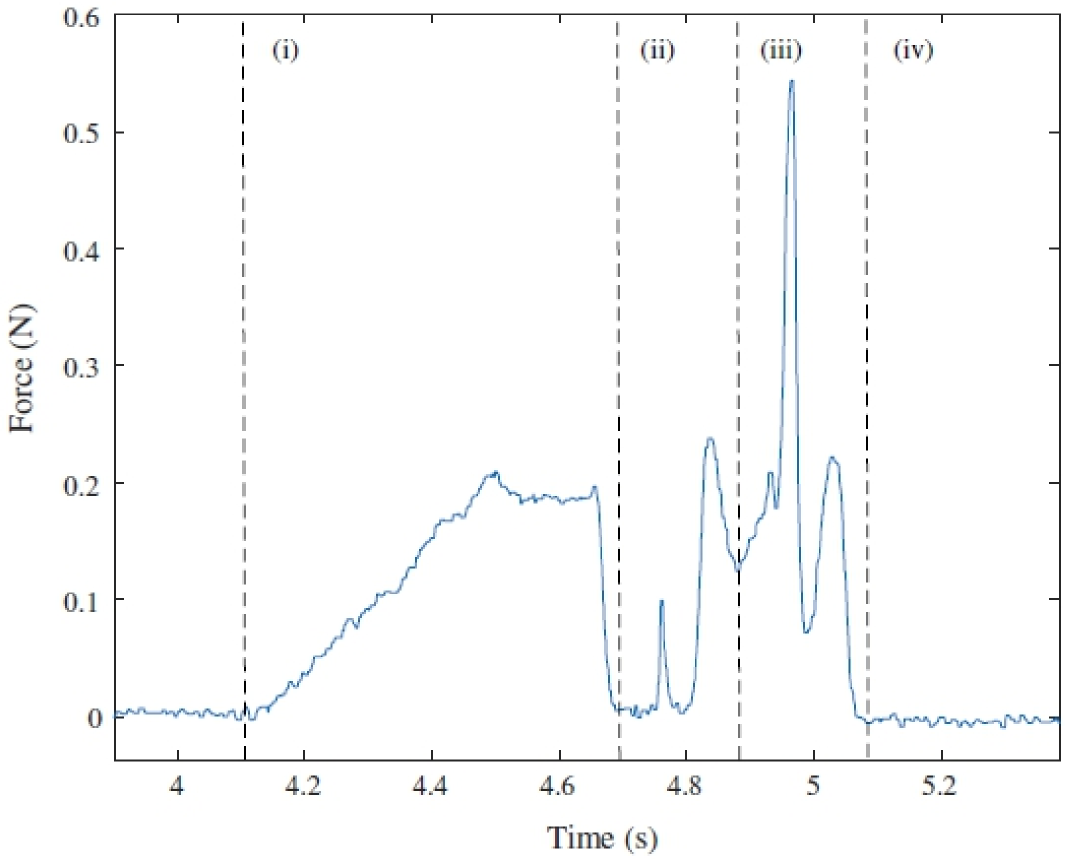
Force Sensors - Applications

- **Force-based Supervisory Controller**
  - Instance correlator
    - To identify each instance during the process according to the force sensor output, the order of the instance (or motion sequences) and the specified conditions
  - Motion sequence selector



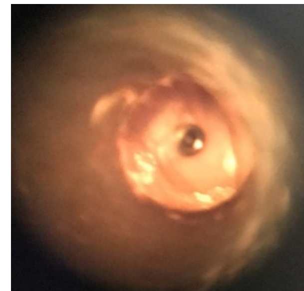
Force Sensors - Applications

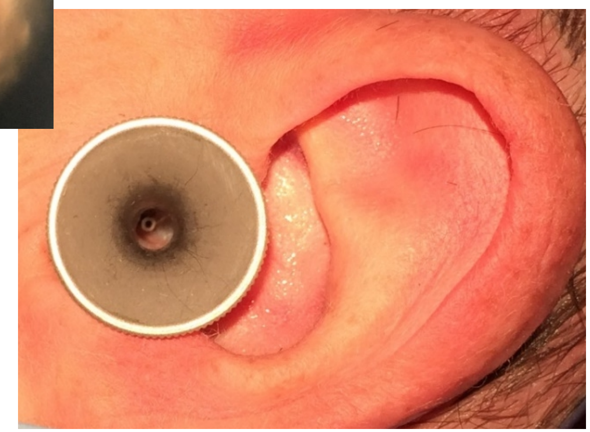
- Force-based Supervisory Controller



Force Sensors - Applications

- **VTA Performance**
  - Success rate **>96%**
  - Insertion time ~1 second

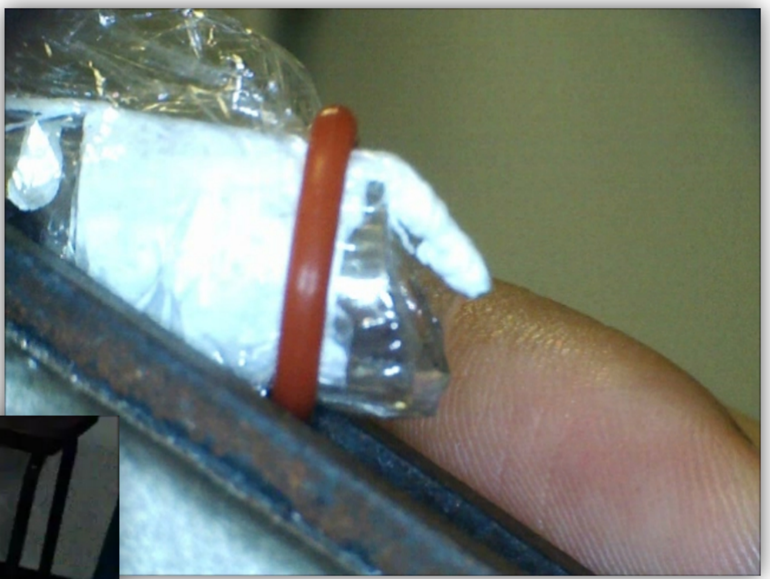


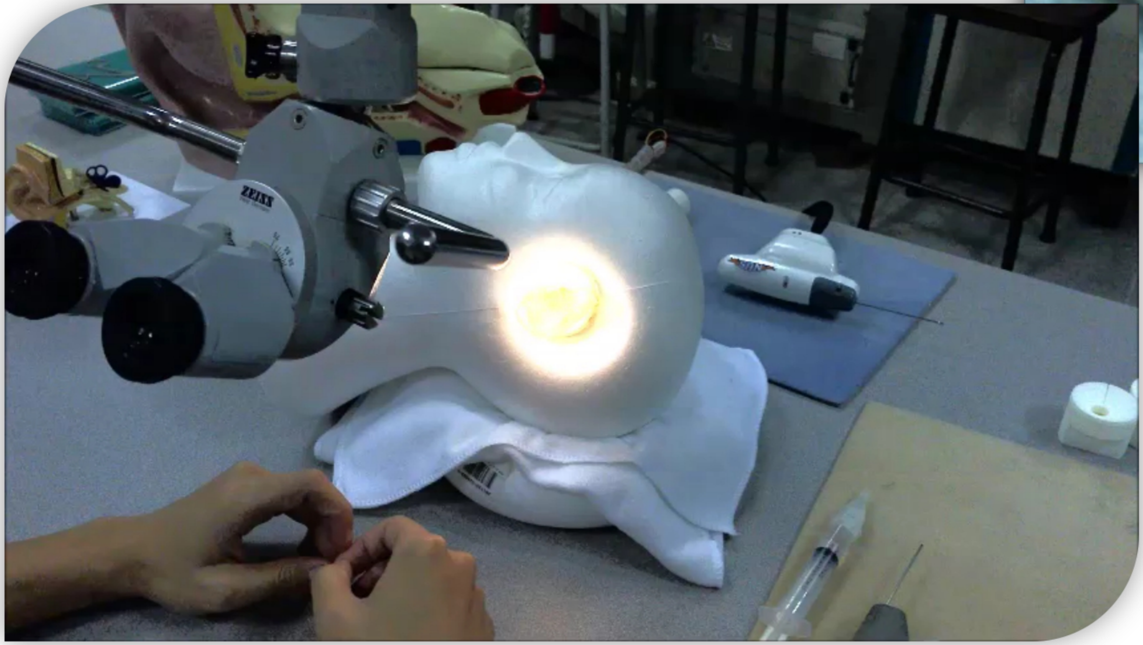


Tiny Tytan grommet

Force Sensors - Applications

- VTA - demo video





Break

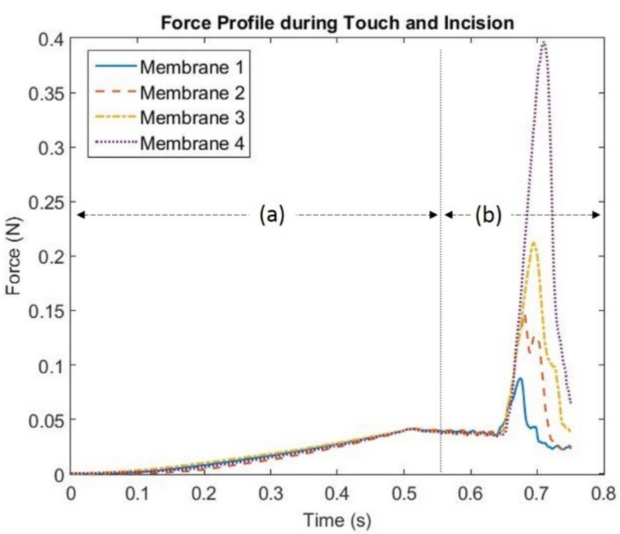
(continue at 11:00)

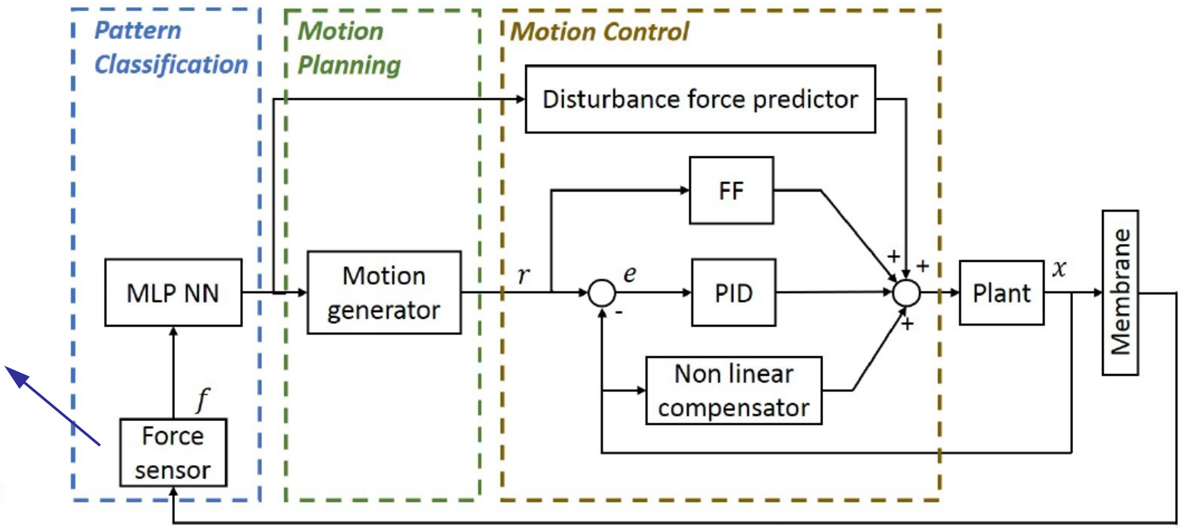
Force Sensors - Applications

Force-based Motion Planning for Robotic Surgery Using Neural Network

Force Sensors - Applications

- **Force-based Motion Planning Using Neural Network (NN)**
  - To account for patient variability, there is a need to identify the biomechanical properties of eardrum before determining the parameters for the grommet insertion path
  - Force sensor readings from the touch and incision sequence are used to differentiate the types of eardrum via Multilevel Perceptron (MLP) NN



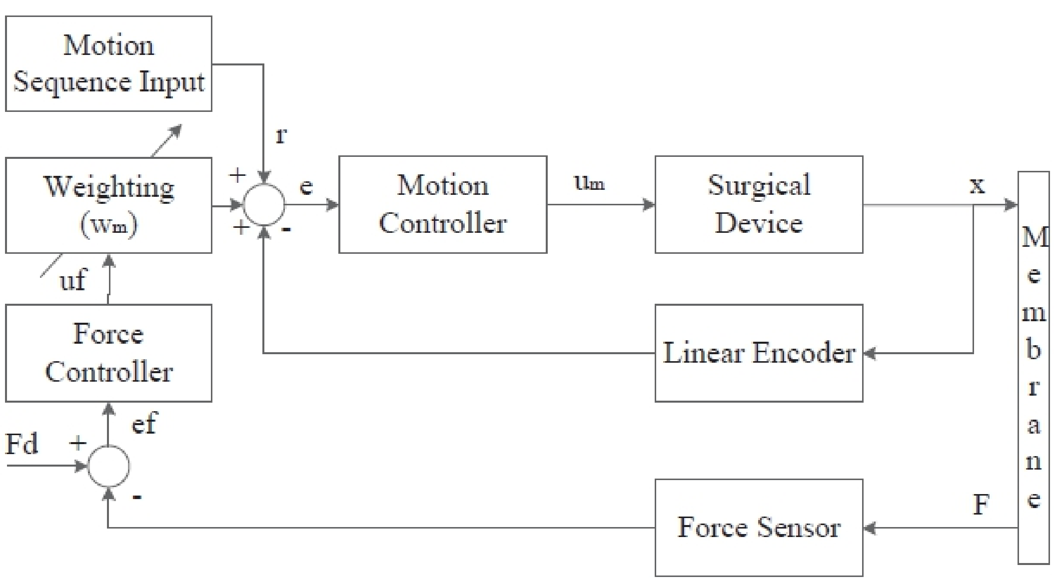


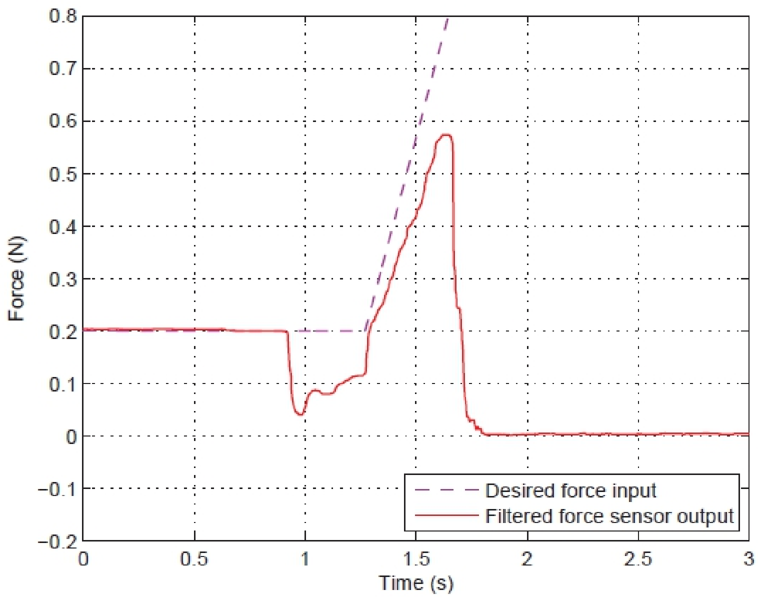
Force Sensors - Applications

Force Feedback Control Assisted Grommet Insertion

Force Sensors - Applications

- **Force Feedback Control Assisted Grommet Insertion**
  - Feed forward mechanism helps to speed up the insertion procedure
  - Force feedback ratio controller guarantees the relatively high success rate in different membranes

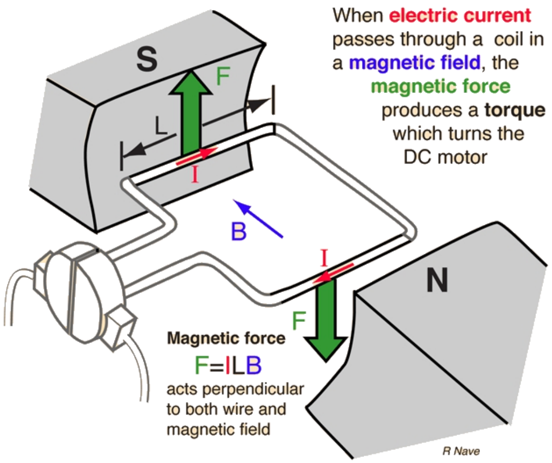


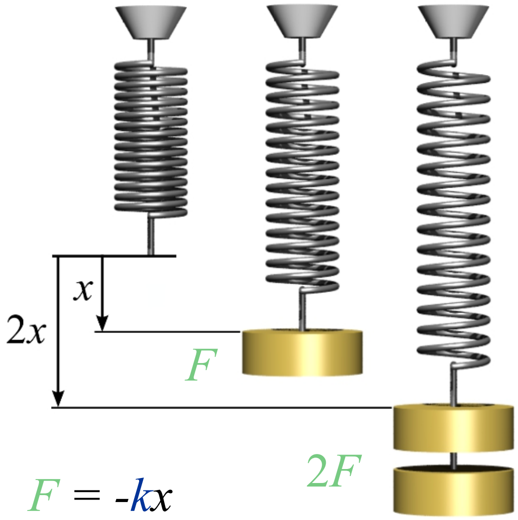


Force Sensorless Estimation

Force Sensing - Some Thoughts

- Possible Force Sensing Methods
  - Current (e.g., DC Motors)
  - Deformation (Hooke's Law)
  - Acceleration (Newton's Second Law)
  - …





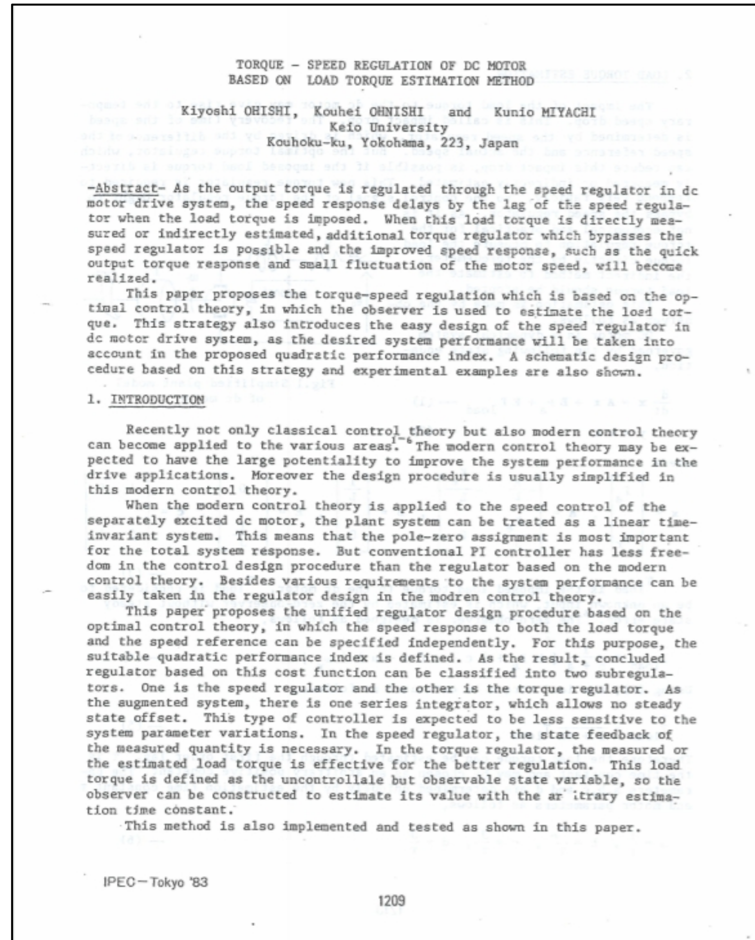
$$F = ma$$

Force Sensorless Estimation

- **Disturbance Observer**
  - A redundant force sensing system can be considered to improve the safety and reliability of a mechatronic system or a device, i.e., another force sensing system can be integrated into the device
    - However, one more force sensing system will increase the weight and size to the overall system which may affect the compact form and portability
  - Sometimes, it is difficult to design and integrate a force sensing system into a mechatronic system or a device (compact, light weight)
  - To detect the force while using the same hardware setup, a Disturbance Observer (DOB) can be considered for addressing this issue

Force Sensorless Estimation

- **Disturbance Observer (DOB)**
  - First proposed by OHISHI *et al.* in 1983
  - A kind of observer that observe or estimate the disturbance
  - One of the most widely used robust control tools
  - Force that is acting on the system can be treated as a **disturbance**



TORQUE – SPEED REGULATION OF DC MOTOR
BASED ON LOAD TORQUE ESTIMATION METHOD

Kiyoshi OHISHI, Kouhei OHNISHI and Kunio MIYACHI
Keio University
Kouhoku-ku, Yokohama, 223, Japan

-Abstract- As the output torque is regulated through the speed regulator in dc motor drive system, the speed response delays by the lag of the speed regulator when the load torque is imposed. When this load torque is directly measured or indirectly estimated, additional torque regulator which bypasses the speed regulator is possible and the improved speed response, such as the quick output torque response and small fluctuation of the motor speed, will become realized.

This paper proposes the torque-speed regulation which is based on the optimal control theory, in which the observer is used to estimate the load torque. This strategy also introduces the easy design of the speed regulator in dc motor drive system, as the desired system performance will be taken into account in the proposed quadratic performance index. A schematic design procedure based on this strategy and experimental examples are also shown.

1. INTRODUCTION

Recently not only classical control theory but also modern control theory can become applied to the various areas.[1-6] The modern control theory may be expected to have the large potentiality to improve the system performance in the drive applications. Moreover the design procedure is usually simplified in this modern control theory.

When the modern control theory is applied to the speed control of the separately excited dc motor, the plant system can be treated as a linear time-invariant system. This means that the pole-zero assignment is most important for the total system response. But conventional PI controller has less freedom in the control design procedure than the regulator based on the modern control theory. Besides various requirements to the system performance can be easily taken in the regulator design in the modren control theory.

This paper proposes the unified regulator design procedure based on the optimal control theory, in which the speed response to both the load torque and the speed reference can be specified independently. For this purpose, the suitable quadratic performance index is defined. As the result, concluded regulator based on this cost function can be classified into two subregulators. One is the speed regulator and the other is the torque regulator. As the augmented system, there is one series integrator, which allows no steady state offset. This type of controller is expected to be less sensitive to the system parameter variations. In the speed regulator, the state feedback of the measured quantity is necessary. In the torque regulator, the measured or the estimated load torque is effective for the better regulation. This load torque is defined as the uncontrollale but observable state variable, so the observer can be constructed to estimate its value with the ar itrary estimation time constant.

This method is also implemented and tested as shown in this paper.

IPEC—Tokyo '83

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Force Sensorless Estimation

- **DOB based Force Estimation**
  - Let's consider the following second-order motion system (e.g., motor)

$$m\ddot{x} = -kx - c\dot{x} + bu - \sigma \mathrm{sign}(\dot{x}) + \eta|\mathrm{sign}(\dot{x})|$$

  - When the external force is applied to the system, the external force can be treated as a kind of external disturbance

$$m\ddot{x} = -kx - c\dot{x} + bu - \sigma \mathrm{sign}(\dot{x}) + \eta|\mathrm{sign}(\dot{x})| + d$$

and

$$\begin{aligned}\ddot{x} &= -\lambda x - \gamma\dot{x} + \beta u + \frac{-\sigma \mathrm{sign}(\dot{x}) + \eta|\mathrm{sign}(\dot{x})|}{m} + \delta \\ &= -G(x,\dot{x}) + F - f_c(\dot{x})/m + \delta\end{aligned}$$

Force Sensorless Estimation

- **DOB based Force Estimation**
  - With a proper motion controller design, we have

$$\ddot{x} = -\lambda x(t) - \gamma \dot{x}(t) + \beta u_{linear}(t) + \delta(t)$$

  - Then, the disturbance can be estimated by

$$\hat{\delta}(t) = \ddot{x}(t) + \lambda x(t) + \gamma \dot{x}(t) - \beta u_{linear}(t)$$

  - In the transfer function form, it becomes

$$D(s) = H_n^{-1}(s) X(s) - U_{linear}(s)$$

$$H_n^{-1}(s) = \frac{s^2 + \gamma s + \lambda}{\beta}$$

Force Sensorless Estimation

- **DOB based Force Estimation**
  - To make $H_n^{-1}(s)$ proper, a low-pass filter is frequently used

$$Q_f(s) = \frac{1}{s^2/\omega_n^2 + s/(q\omega_n) + 1}$$

  - Finally, the disturbance can be estimated by the following equation

$$\hat{\delta}(s) = [H_n^{-1}(s)Q_f(s)X(s) - U_{linear}(s)Q_f(s)]$$

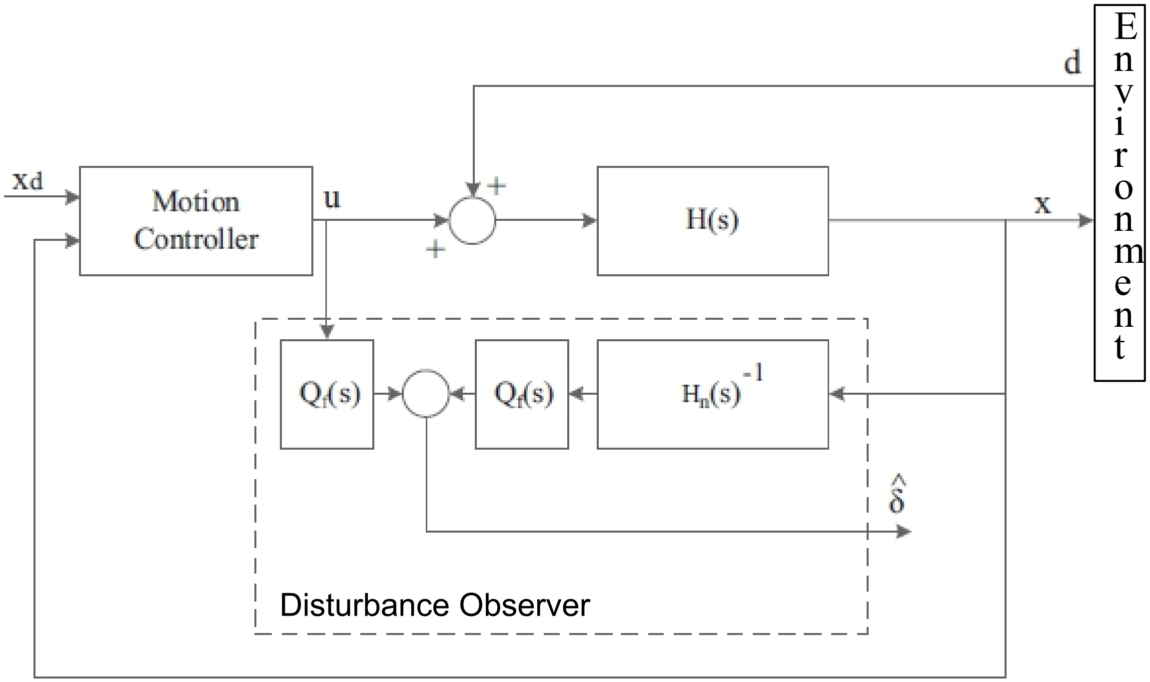
  - If $Q_f(s) \approx 1$, then

$$\Downarrow \approx$$

$$H_n^{-1}(s)X(s) - U_{linear}(s)$$

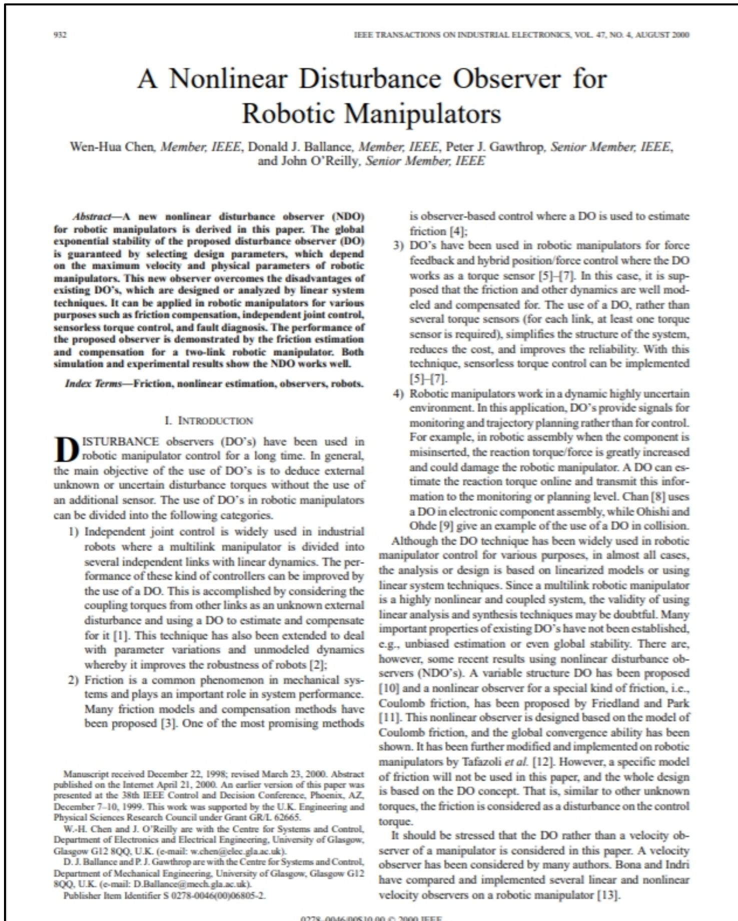
Force Sensorless Estimation

- DOB based Force Estimation
  - How to design the low-pass filter?



Force Sensorless Estimation

- **Nonlinear Disturbance Observer (NDOB)**
  - First proposed by CHEN *et al.* in 2000
  - It can be used in nonlinear system
  - Application areas
    - Independent joint control
    - Sensorless force/torque control
    - Fault diagnosis in robotics



932 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 47, NO. 4, AUGUST 2000

A Nonlinear Disturbance Observer for Robotic Manipulators

Wen-Hua Chen, *Member, IEEE*, Donald J. Ballance, *Member, IEEE*, Peter J. Gawthrop, *Senior Member, IEEE*, and John O'Reilly, *Senior Member, IEEE*

***Abstract*—A new nonlinear disturbance observer (NDO) for robotic manipulators is derived in this paper. The global exponential stability of the proposed disturbance observer (DO) is guaranteed by selecting design parameters, which depend on the maximum velocity and physical parameters of robotic manipulators. This new observer overcomes the disadvantages of existing DO's, which are designed or analyzed by linear system techniques. It can be applied in robotic manipulators for various purposes such as friction compensation, independent joint control, sensorless torque control, and fault diagnosis. The performance of the proposed observer is demonstrated by the friction estimation and compensation for a two-link robotic manipulator. Both simulation and experimental results show the NDO works well.**

***Index Terms*—Friction, nonlinear estimation, observers, robots.**

I. Introduction

Disturbance observers (DO's) have been used in robotic manipulator control for a long time. In general, the main objective of the use of DO's is to deduce external unknown or uncertain disturbance torques without the use of an additional sensor. The use of DO's in robotic manipulators can be divided into the following categories.

1) Independent joint control is widely used in industrial robots where a multilink manipulator is divided into several independent links with linear dynamics. The performance of these kind of controllers can be improved by the use of a DO. This is accomplished by considering the coupling torques from other links as an unknown external disturbance and using a DO to estimate and compensate for it [1]. This technique has also been extended to deal with parameter variations and unmodeled dynamics whereby it improves the robustness of robots [2];
2) Friction is a common phenomenon in mechanical systems and plays an important role in system performance. Many friction models and compensation methods have been proposed [3]. One of the most promising methods is observer-based control where a DO is used to estimate friction [4];
3) DO's have been used in robotic manipulators for force feedback and hybrid position/force control where the DO works as a torque sensor [5]–[7]. In this case, it is supposed that the friction and other dynamics are well modeled and compensated for. The use of a DO, rather than several torque sensors (for each link, at least one torque sensor is required), simplifies the structure of the system, reduces the cost, and improves the reliability. With this technique, sensorless torque control can be implemented [5]–[7].
4) Robotic manipulators work in a dynamic highly uncertain environment. In this application, DO's provide signals for monitoring and trajectory planning rather than for control. For example, in robotic assembly when the component is misinserted, the reaction torque/force is greatly increased and could damage the robotic manipulator. A DO can estimate the reaction torque online and transmit this information to the monitoring or planning level. Chan [8] uses a DO in electronic component assembly, while Ohishi and Ohde [9] give an example of the use of a DO in collision.

Although the DO technique has been widely used in robotic manipulator control for various purposes, in almost all cases, the analysis or design is based on linearized models or using linear system techniques. Since a multilink robotic manipulator is a highly nonlinear and coupled system, the validity of using linear analysis and synthesis techniques may be doubtful. Many important properties of existing DO's have not been established, e.g., unbiased estimation or even global stability. There are, however, some recent results using nonlinear disturbance observers (NDO's). A variable structure DO has been proposed [10] and a nonlinear observer for a special kind of friction, i.e., Coulomb friction, has been proposed by Friedland and Park [11]. This nonlinear observer is designed based on the model of Coulomb friction, and the global convergence ability has been shown. It has been further modified and implemented on robotic manipulators by Tafazoli *et al.* [12]. However, a specific model of friction will not be used in this paper, and the whole design is based on the DO concept. That is, similar to other unknown torques, the friction is considered as a disturbance on the control torque.

It should be stressed that the DO rather than a velocity observer of a manipulator is considered in this paper. A velocity observer has been considered by many authors. Bona and Indri have compared and implemented several linear and nonlinear velocity observers on a robotic manipulator [13].

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Force Sensorless Estimation

- **NDOB based Force Estimation**
  - An auxiliary variable z is defined as

$$\begin{cases} z = \hat{\delta} - p(y) \\ \dot{z} = -l(y)z + l(y)[G(x,\dot{x}) - \beta u_{linear} - p(y)] \\ y = C\dot{x} \end{cases}$$

where (p.s. $C = 1$) L is a positive constant and

$$l(y) = \frac{\partial p(y)}{\partial y} \qquad p(y) = Ly = L\dot{x}$$

  - Then, the observer gain function becomes

$$l(y) = \frac{\partial}{\partial y}(Ly) = L$$

Force Sensorless Estimation

- **NDOB based Force Estimation**
  - Hence, the system can be rewritten as

$$
\begin{aligned}
\dot{z} &= -Lz + L[G(x,\dot{x}) - \beta u_{linear} - p(\dot{x})] \\
&= -Lz + L[\lambda x + \gamma \dot{x} - \beta u_{linear} - p]
\end{aligned}
$$

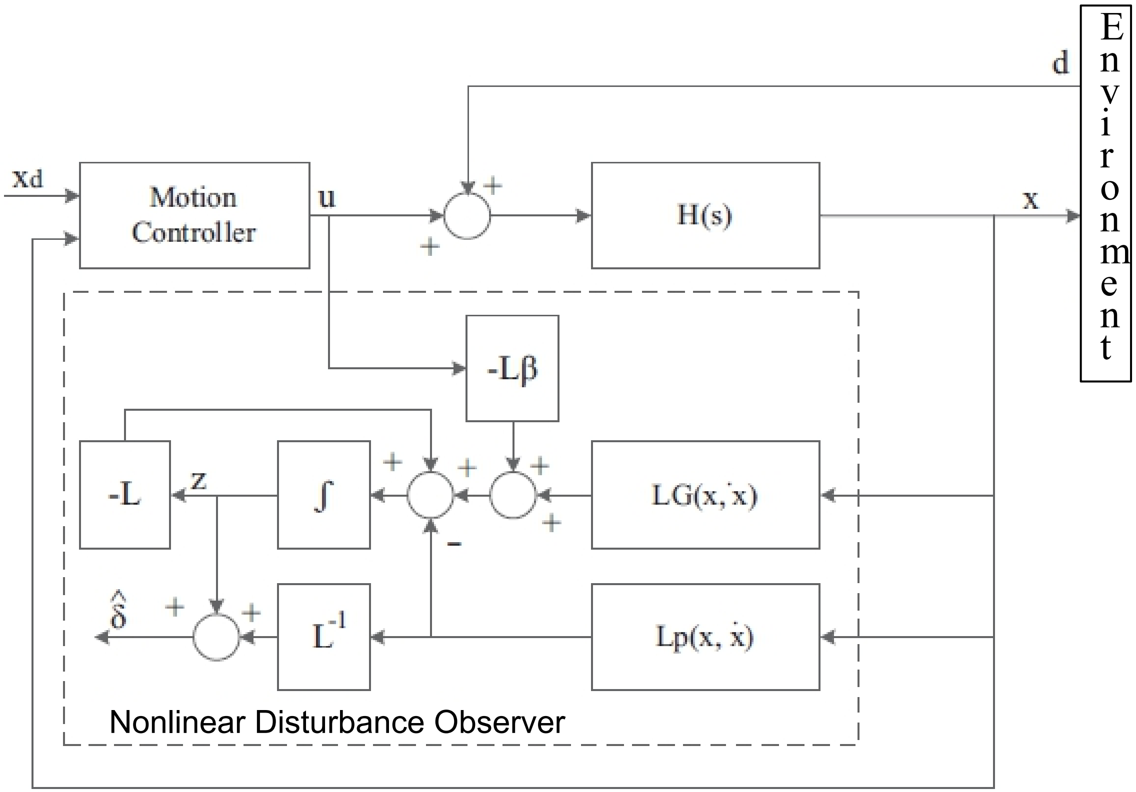
$$\dot{p}(y) = L\ddot{x}$$

  - and the disturbance can be estimated by the following equation

$$\boxed{-\hat{\delta} = -z - p}$$

Force Sensorless Estimation

- **NDOB based Force Estimation**
  - How to design the observer gain?



Force Sensorless Estimation

- **NDOB based Force Estimation**
  - Here, one of the disturbance observer goals is to minimize the observer error

$$\tilde{\delta} = \delta - \hat{\delta}$$

  - Two cases:
    - Constant disturbance

$$\dot{\delta} = 0$$

    - Varying disturbance

$$\dot{\delta} \neq 0$$

Lyapunov Theory

Lyapunov Theory

- **Lyapunov's Direct Method**
  - Consider continuously differentiable function $V(x)$ such that
    - $V(0) = 0$
    - $V(x) > 0$ for $x \neq 0$

      (positive definite)

    and
    - $\dot{V}(x) \leq 0$ for $x \neq 0$
  - Then, the system is stable in the sense of Lyapunov
  - Moreover, if $\dot{V}(x) < 0$ for $x \neq 0$, then the system is asymptotically stable

Force Sensorless Estimation

- **NDOB based Force Estimation**
  - Consider a Lyapunov function as

$$V = \frac{1}{2}\tilde{\delta}^2$$

  - Time derivative of the Lyapunov function is

$$\dot{V} = \tilde{\delta}\dot{\tilde{\delta}}$$

Force Sensorless Estimation

- **NDOB based Force Estimation**
  - Since $\hat{\delta} = -z - p$, we have

$$
\begin{aligned}
\dot{\tilde{\delta}} &= \dot{\delta} - \dot{\hat{\delta}} = \dot{\delta} - \dot{z} - \dot{p} \\
&= \dot{\delta} + Lz - L(\lambda x + \gamma \dot{x} - \beta u_{linear} - p) - L\ddot{x} \\
&= \dot{\delta} + Lz - L(\delta - \ddot{x}) - Lp - L\ddot{x} \\
&= \dot{\delta} + Lz - L\delta + Lp \\
&= \dot{\delta} - L(\delta - z - p) \\
&= \dot{\delta} - L(\delta - \hat{\delta}) = \dot{\delta} - L\tilde{\delta}
\end{aligned}
$$

  - Therefore,

$$\dot{V} = \tilde{\delta}(\dot{\delta} - L\tilde{\delta}) = -L\tilde{\delta}^2 + \tilde{\delta}\dot{\delta}$$

Force Sensorless Estimation

- **NDOB based Force Estimation**

$$\dot{V} = \tilde{\delta}(\dot{\delta} - L\tilde{\delta}) = -L\tilde{\delta}^2 + \tilde{\delta}\dot{\delta}$$

  - For constant disturbance case, it is easy to have

$$\dot{V} = -L\tilde{\delta}^2 \leq 0$$

and

$$\tilde{\delta}(t) = \Gamma e^{-Lt}$$

    - The observer error can converge to zero and the estimated disturbance can approach to the actual constant disturbance

Force Sensorless Estimation

- **NDOB based Force Estimation**

$$\dot{V} = \tilde{\delta}(\dot{\delta} - L\tilde{\delta}) = -L\tilde{\delta}^2 + \tilde{\delta}\dot{\delta}$$

  - For varying disturbance case,

$$\begin{aligned}\dot{V} =& -L\tilde{\delta}^2 + \tilde{\delta}\dot{\delta} \\ \leq& -L\tilde{\delta}^2 + |\tilde{\delta}\dot{\delta}| = -L|\tilde{\delta}|^2 + |\tilde{\delta}||\dot{\delta}| \\ \leq& -L|\tilde{\delta}|^2 + |\tilde{\delta}|\Delta_m \\ =& -|\tilde{\delta}|(L|\tilde{\delta}| - \Delta_m)\end{aligned}$$

    - The time derivative of the Lyapunov function is negative as long as the inequality $(L|\tilde{\delta}| - \Delta_m)$ is met

$$\dot{V} < -|\tilde{\delta}| < 0, \ \forall|\tilde{\delta}| > \Delta_m/L$$

Force Sensorless Estimation

- **NDOB based Force Estimation**

$$\dot{V} = \tilde{\delta}(\dot{\delta} - L\tilde{\delta}) = -L\tilde{\delta}^2 + \tilde{\delta}\dot{\delta}$$

- For varying disturbance case,

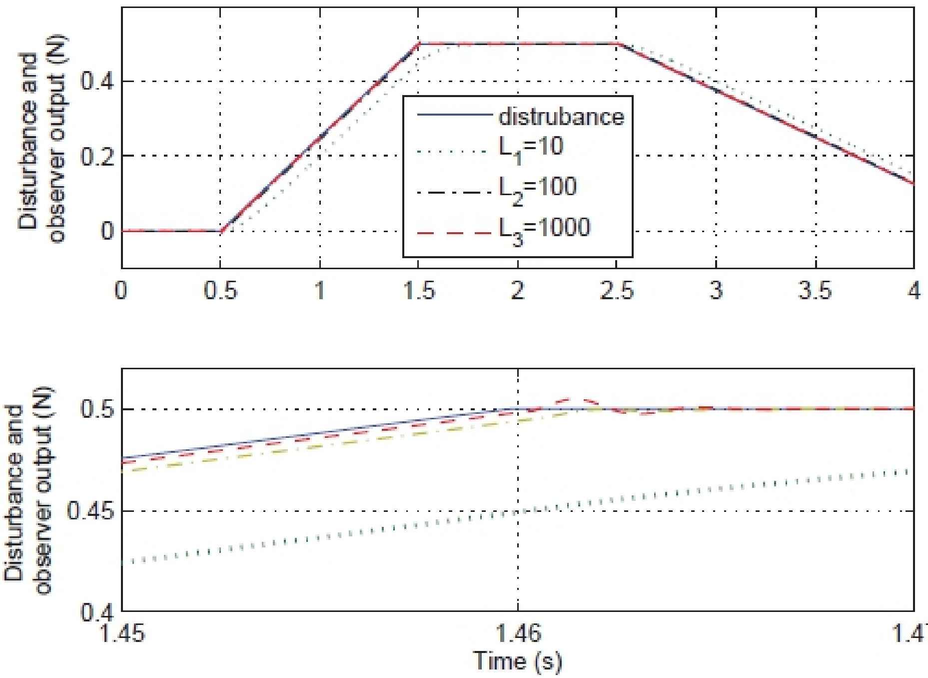
$$\dot{V} < -|\tilde{\delta}| < 0, \ \forall|\tilde{\delta}| > \Delta_m/L$$

  - The observer error is uniformly bounded
  - In other words, all the solutions that start outside of the compact set $B_\Delta = \{|\tilde{\delta}| \leq \Delta_m/L\}$ (i.e., $\dot{V} < 0$) will enter this set in a finite time and remain inside it in the future for all time
  - A **small** observer error can be achieved by selecting a **large** observer gain

Force Sensorless Estimation

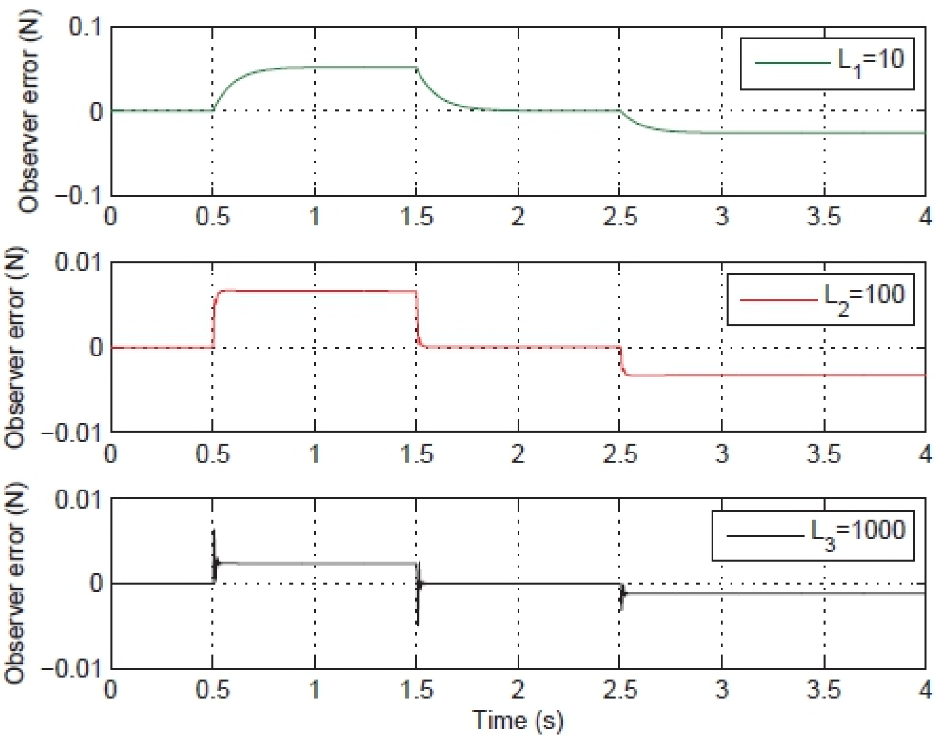
- **NDOB based Force Estimation - Simulation**
  - VTA is used as the system contacting with the environment
  - Environment model employed in the simulation

$$\delta_s = \begin{cases} k_s x \ , & x > 0 \\ 0 \ , & x \leq 0 \end{cases}$$



Force Sensorless Estimation

- **NDOB based Force Estimation - Simulation**
  - Observer error

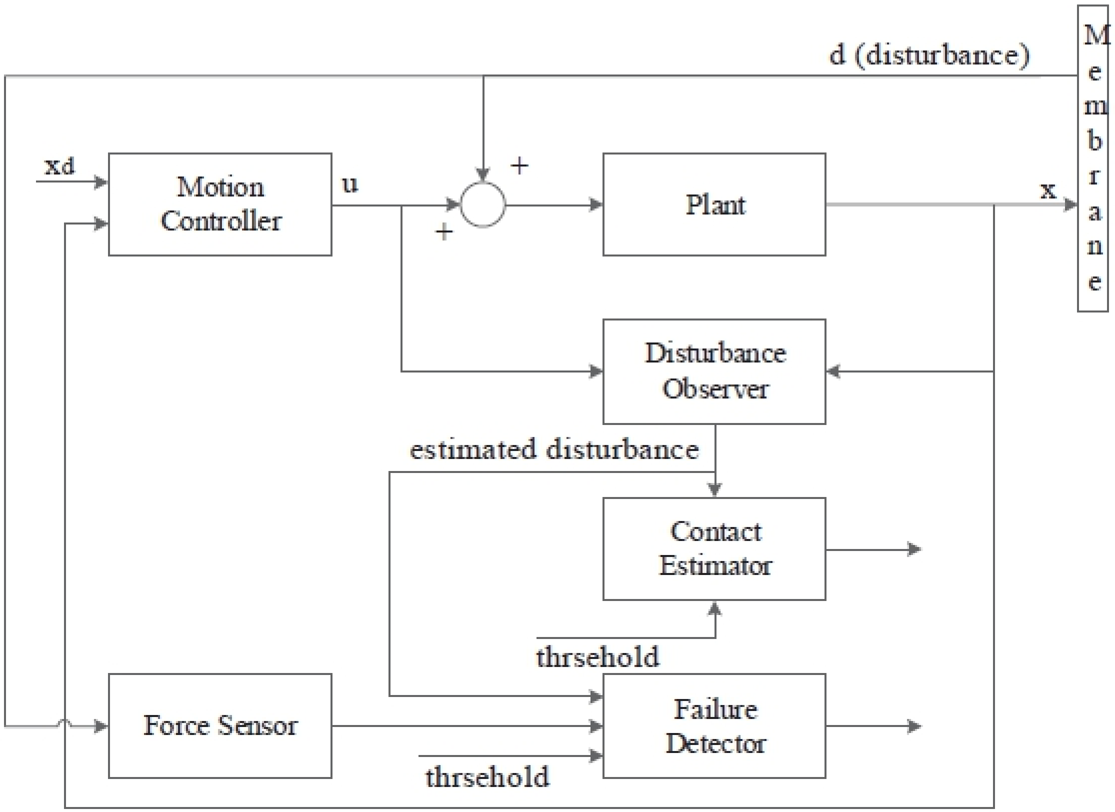


Force Sensorless Estimation - Applications

Force Estimation & Failure Detection for An Ear Surgical Device

Force Sensorless Estimation - Applications

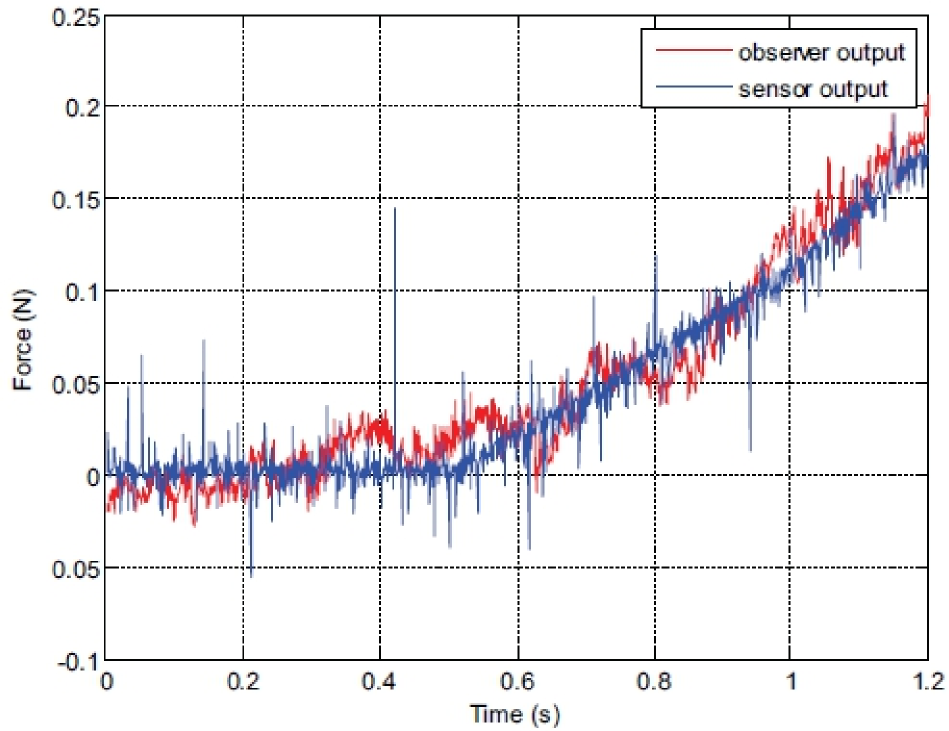
- Force Estimation & Failure Detection



Force Sensorless Estimation - Applications

- Touch Detection

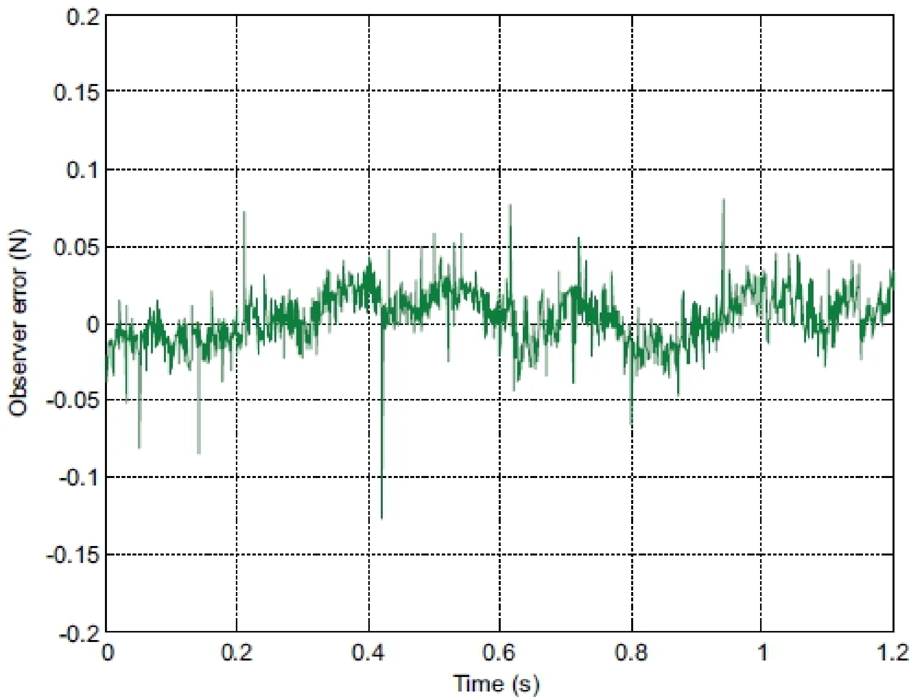
$$S_c = \begin{cases} 0\ , & |\hat{\delta}| < \epsilon \\ 1\ , & \text{otherwise} \end{cases}$$



Force Sensorless Estimation - Applications

- Touch Detection

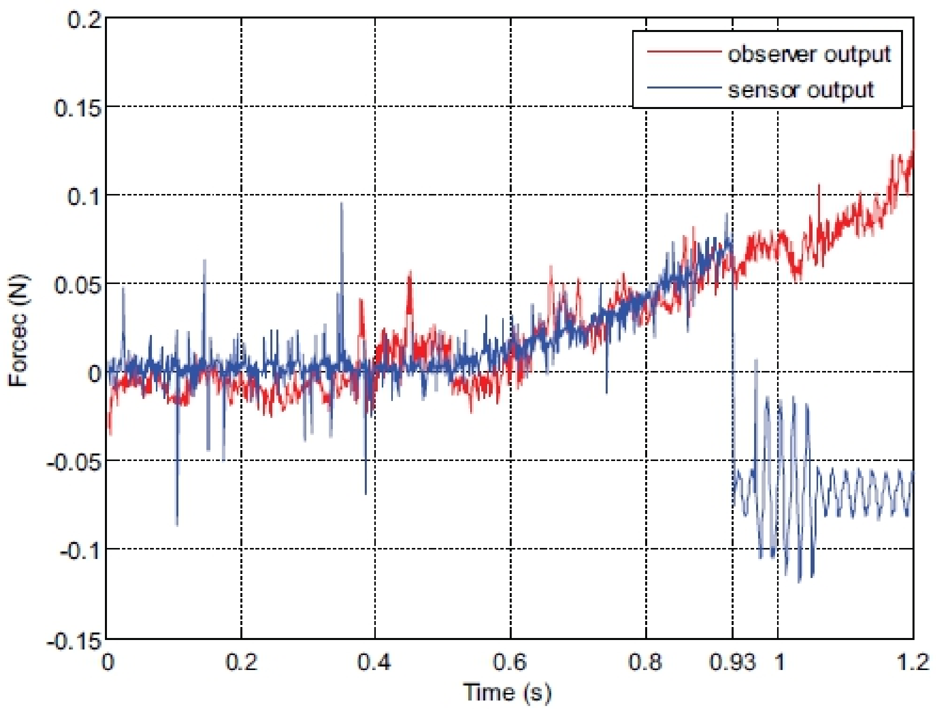
$$S_c = \begin{cases} 0\ , & |\hat{\delta}| < \epsilon \\ 1\ , & \text{otherwise} \end{cases}$$



Force Sensorless Estimation - Applications

- Sensor Failure Detection

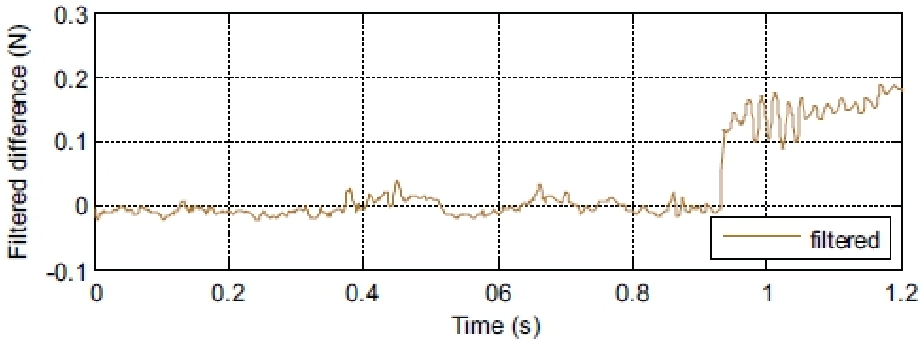
$$S_f = \begin{cases} 0\ , & |\bar{\delta} - \hat{\delta}| < \sqrt{\varpi} \\ 1\ , & \text{otherwise} \end{cases}$$



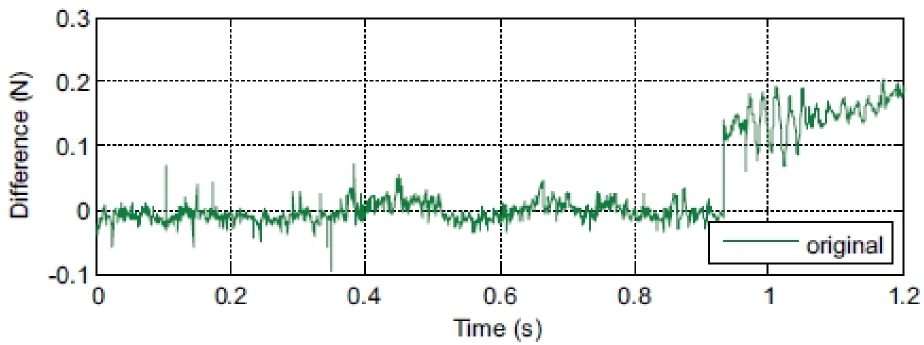
Force Sensorless Estimation - Applications

- Sensor Failure Detection

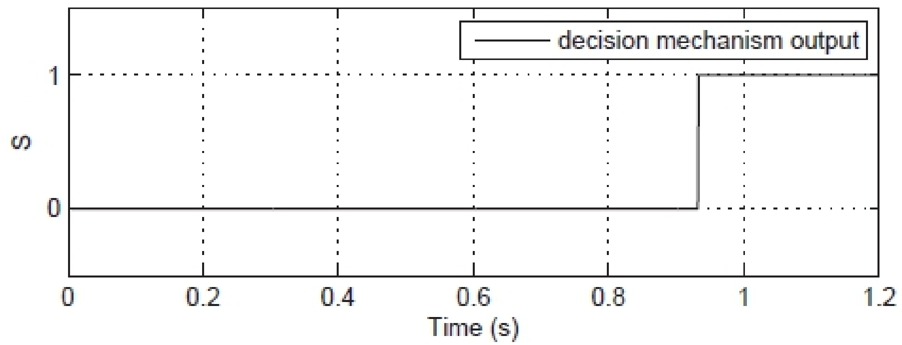
$$S_f = \begin{cases} 0\,, & |\bar{\delta} - \hat{\delta}| < \sqrt{\varpi} \\ 1\,, & \text{otherwise} \end{cases}$$



(b) filtered difference



(a) actual difference



(c) output of decision mechanism

Force Sensorless Estimation

- **To Think about (while Using Disturbance Observer)…**
  - How to select the optimal parameters?
  - Some other forces can also be considered as external disturbance, how?
    - Gravity force
    - Frictional force

> - S. Huang, W. Liang and K. K. Tan, "Intelligent Friction Compensation: A Review," *IEEE/ASME Transactions on Mechatronics,* vol. 24, no. 4, pp. 1763-1774, Aug. 2019
> - T. H. Lee, W. Liang, K. K. Tan, and C. W. de Silva, "Force and Position Control of Mechatronic Systems: Design and Applications in Medical Devices," Springer Nature, 2020

  - Model is not accurate?

Force Sensorless Estimation

Other Ideas

Force Sensorless Estimation - Other Ideas

- **Extended State Observer (ESO)**
  - First proposed by HAN in the 1990s (in Chinese)
  - Basic idea:

$$\ddot{x} + b\dot{x} + kx + d = hu$$

$$f = -b\dot{x} - kx - d$$

$$\begin{aligned} x &= x_1, \\ \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3 + hu, \\ &= f + hu, \\ \dot{x}_3 &= \dot{f}, \end{aligned}$$

$$\boxed{\begin{aligned} \dot{x}_{e1} &= x_{e2} + l_1(x_1 - x_{e1}), \\ \dot{x}_{e2} &= x_{e3} + l_2(x_1 - x_{e1}) + hu, \\ \dot{x}_{e3} &= l_3(x_1 - x_{e1}) + \dot{\hat{f}}, \\ [l_1, l_2, l_3] &= [\omega_0\alpha_1, \omega_0^2\alpha_2, \omega_0^3\alpha_3] \end{aligned}}$$

900 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 56, NO. 3, MARCH 2009

From PID to Active Disturbance Rejection Control

Jingqing Han

***Abstract*—Active disturbance rejection control (ADRC) can be summarized as follows: it inherits from proportional–integral–derivative (PID) the quality that makes it such a success: the error driven, rather than model-based, control law; it takes from modern control theory its best offering: the state observer; it embraces the power of nonlinear feedback and puts it to full use; it is a useful digital control technology developed out of an experimental platform rooted in computer simulations. ADRC is made possible only when control is taken as an experimental science, instead of a mathematical one. It is motivated by the ever increasing demands from industry that requires the control technology to move beyond PID, which has dominated the practice for over 80 years. Specifically, there are four areas of weakness in PID that we strive to address: 1) the error computation; 2) noise degradation in the derivative control; 3) oversimplification and the loss of performance in the control law in the form of a linear weighted sum; and 4) complications brought by the integral control. Correspondingly, we propose four distinct measures: 1) a simple differential equation as a transient trajectory generator; 2) a noise-tolerant tracking differentiator; 3) the nonlinear control laws; and 4) the concept and method of total disturbance estimation and rejection. Together, they form a new set of tools and a new way of control design. Times and again in experiments and on factory floors, ADRC proves to be a capable replacement of PID with unmistakable advantage in performance and practicality, providing solutions to pressing engineering problems of today. With the new outlook and possibilities that ADRC represents, we further believe that control engineering may very well break the hold of classical PID and enter a new era, an era that brings back the spirit of innovations.**

***Index Terms*—Active disturbance rejection control (ADRC), extended state observer (ESO), nonlinear proportional–integral–derivative (PID), tracking differentiator.**

I. Introduction

THE BIRTH and large-scale deployments of the powerful yet primitive proportional–integral–derivative (PID) control law dates back to the period of the 1920s–1940s in the last century, in response to the pressing demands of industrial automation before, during, and particularly after World War II. Its role in the explosive growth in the postwar manufacturing industry is unmistakable; its dominance is evident even today across various sectors of the entire industry. It is at the same time undeniable that PID is increasingly overwhelmed by the new demands in this era of modern industries where the unending pursuit of efficiency and the lack and cost of skilled labor put a high premium on feedback control technologies. Its merit of simplicity in the analog electronics era has turned into a liability in the digital control one as it cannot fully take advantage of the new compact and powerful digital processors. It appears that, as any technology, PID will eventually outlive its usefulness, if it has not already done so. The question is, what will replace this hugely successful control mechanism in the 21st century, retaining its basic soundness and, at the same time, shedding its limitations? It is doubtful that such question was even entertained systematically, let alone answered, in the past.

We believe that the answer lies in our understanding of both the characteristics of PID and the challenges it faces. It is such understanding that will lead us to propose further developments in the PID framework and, perhaps, even a drastic innovation toward a new generation of digital control solutions. In this paper, we suggest that there are four fundamental technical limitations in the existing PID framework, and we proceed to propose the corresponding technical and conceptual solutions, including the following: 1) a simple differential equation to be used as a transient profile generator; 2) a noise-tolerant tracking differentiator; 3) the power of nonlinear control feedback; and 4) the total disturbance estimation and rejection. Together, these new tools combine to form the backbone of a new synthesis of digital control law that is not predicated on an accurate and detailed dynamic model of the plant and is extremely tolerant of uncertainties and simple to use. Moreover, we denote this new synthesis active disturbance rejection control or ADRC.

ADRC has been a work in progress for almost two decades [1]–[7], with its ideas and applications appearing in the English literature, amid some questions and confusions, sporadically only in recent years; see, for example, [8]–[14]. In ADRC, we see a paradigmatic change in feedback control that was first systematically introduced in English in 2001 [8]. The conception of active disturbance rejection was further elaborated in [9]. However, even though much success has been achieved in practical applications of ADRC, it appears that this new paradigm has not been well understood and there is a need for a paper that provides a full account of ADRC to the English audience [13]. Such need is unmistakable in the recently proposed terminologies such as equivalent input disturbance [14] and disturbance input decoupling [15], all of which can be seen as a special case of ADRC where only the external disturbance was considered. It is primarily for this reason that this paper is written.

In this paper, we start with, in Section II, classical PID, a dominant technology in industry today, and discuss its characteristics and weaknesses, followed by the proposed remedies in Section III and the resulting ADRC control scheme in Section IV. How this new framework is used to solve various kinds of control problems is shown in Section V. To further help users master this new methodology, some key points in the application of ADRC are presented in Section VI, followed by the concluding remarks in Section VII.

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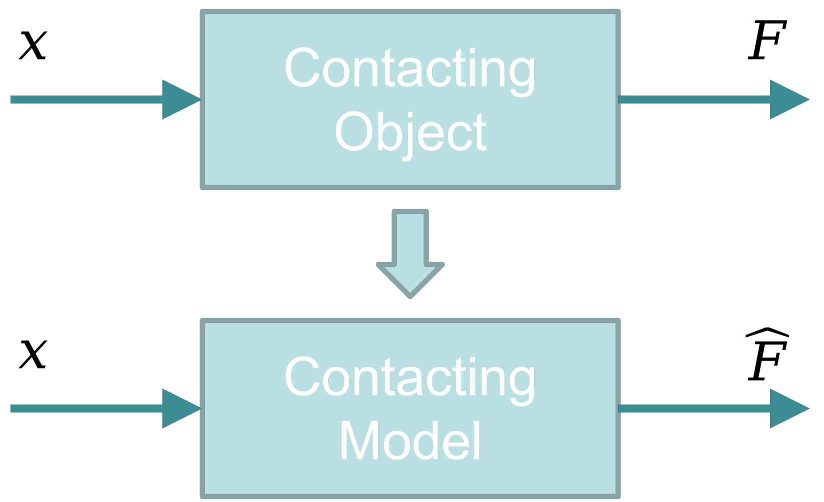
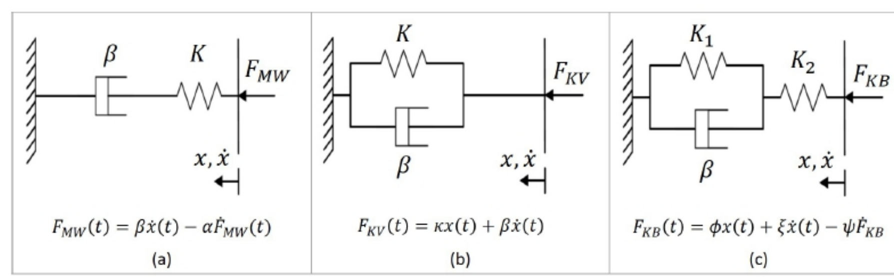
Force Sensorless Estimation - Other Ideas

- **Model-based Force Estimation**



  - Linear Model (spring-dashpot)
    - Maxwell
    - Kelvin-Voigt
    - Kelvin-Boltzmann



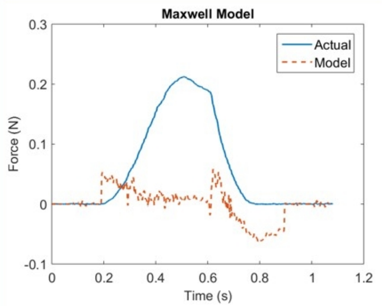
  - Nonlinear Model
    - Hunt-Crossley

$$F_{HC} = Kx^n(t) + \lambda x^n(t)\dot{x}(t)$$

Force Sensorless Estimation - Other Ideas

- **Model-based Force Estimation**
  - Force Model Comparison on Soft Membrane

Maxwell	Kelvin-Voigt	Kelvin-Boltzmann	Hunt-Crossley

Maxwell


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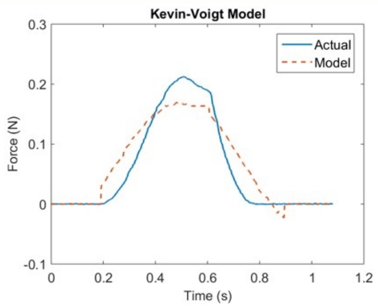
Kelvin-Voigt


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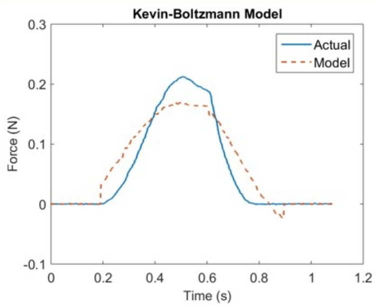

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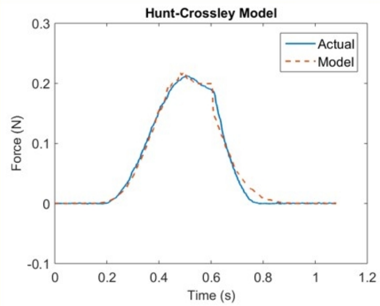
Hunt-Crossley


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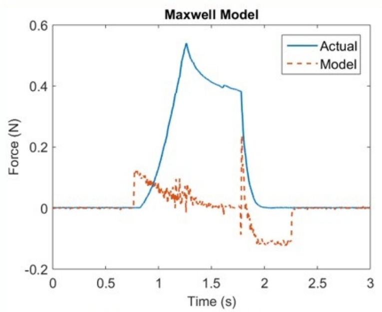
Maxwell


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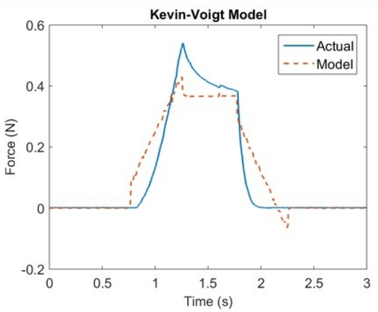
Kelvin-Voigt


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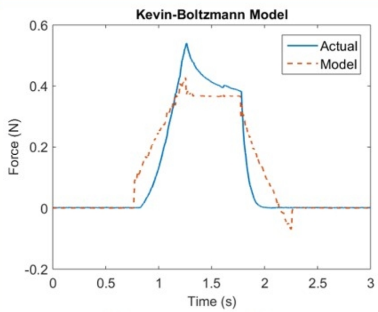
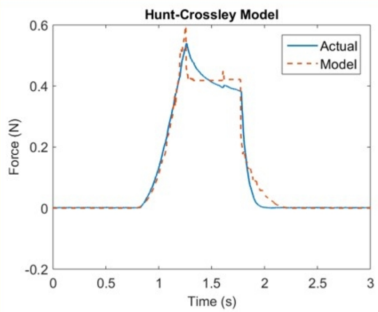
Kelvin-Boltzmann


Fit = 64.21%

Hunt-Crossley


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Summary

- **Force Sensors**
  - Strain Gauge (Load Cell)
  - Force Sensing Resistor
  - Piezoelectric Force Sensors
  - Other Force Sensors
- **Force Sensorless Estimation**
  - Disturbance Observer
  - Nonlinear Disturbance Observer
  - Other ideas
    - Extended State Observer
    - Contacting Model-based Estimation

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Assessment

- **Please check the "CAs (EE5111/5060)" folder in LumiNUS**
  - The first part (CA3a) of my assignment will be uploaded on this Friday (Sep. 17, 2020)

Folder Name	Opening Date	Expiry Date	Status	
CAs (EE5111/5060)	22 Jul 2021 11:21 am	2 Jan 2022 12:00 am	Open	...
CAs (EE5111/5061)	22 Jul 2021 11:22 am	2 Jan 2022 12:00 am	Open	...
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- **Submission Method**
  - Soft copy (Word or .pdf)
- **Submission deadline:**
  - Friday (Oct. 8, 2020) of the second week after recess week

Folder Name	Opening Date	Expiry Date	Status	
CA3a - Submission Submission Submit before 8 Oct 2021 11:59 pm	17 Sep 2021 12:00 pm	8 Oct 2021 11:59 pm	Closed	...

Assessment

- CA3a sample

EE5111/5060 Selected Topics in Industrial Control & Instrumentation

CA3a Assignment for Force Sensing

(Academic Year 2021/22, Semester I)

This assignment will contribute 5% to the total marks for the module EE5111 and 10% for EE5060.
Please make sure your CA3a report is clear and readable.
Please submit your CA3a report (soft copy: Word or .pdf) into the "CA3a - Submission" folder in LumiNUS.
Submission deadline: **Oct. 8, 2020**
Important: Each submitted CA3a report must be an individual report.

1. A force sensor is used to measure a contact force which range is from 0 to x N. The specifications of the force sensor are shown as follows. An instrumentation amplifier is used to amplify the force sensor output signal to an analog-to-digital converter (ADC). The of the ADC is from -10 to 10 V.

Table I Force sensor specifications

Characteristic	Unit	
Excitation	V	10
Force sensing range	N	0 to 5
Sensitivity	mV/N	60
Safe overload	N	10

Please analysis this force sensing application and design the amplifier gain and the gain resistor (R_G) of the instrumentation amplifier as shown in Fig. 1 (where $R_1 = R_2 = 25$ kΩ).

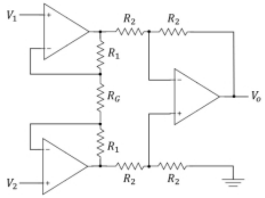

Figure 1 Block diagram of an instrumentation amplifier

1 of 1

All the best!