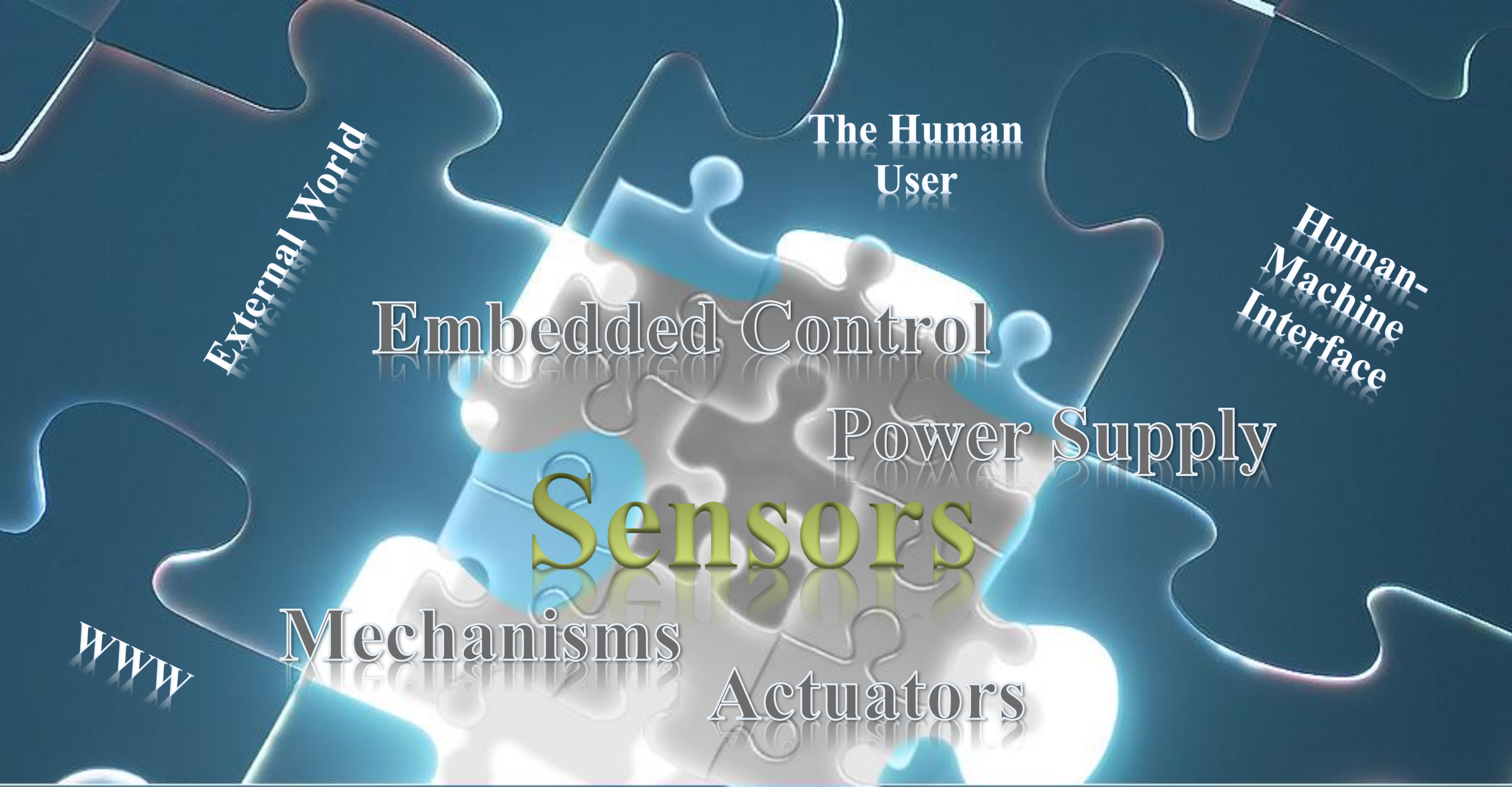


John-John Cabibihan, Ph.D.
Asst. Professor, Dept. of Electrical and Computer Engineering
National University of Singapore

Lecture Outline

1. PPS Capacitive sensors
2. CyberGlove – bend sensing sensors
3. Polhemus motion tracking system
4. Potentiometric sensors
5. IR sensors
6. Contact sensors
7. Tri-axial force sensors
8. Strain gages
9. Machine vision

Capacitive Sensors

The basic operation of a capacitive sensor can be seen from the familiar equation for a parallel-plate capacitor:

$$C = K\varepsilon_0 \frac{A}{d}$$

where,

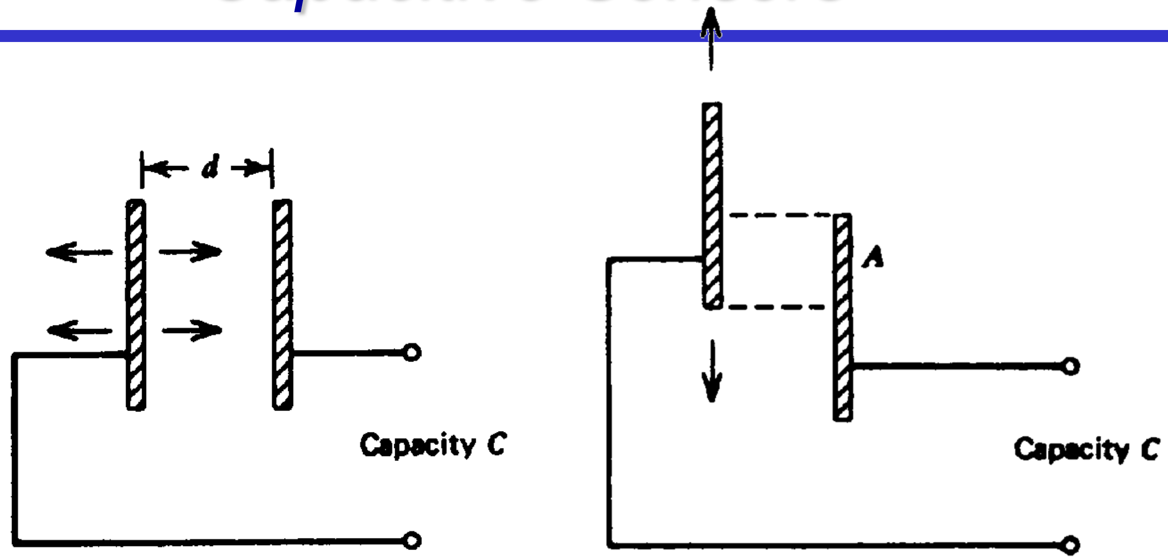
K = the dielectric constant (equals 1 for air);

ε_0 = permittivity (8.85 pF/m);

A = plate common area;

d = plate separation.

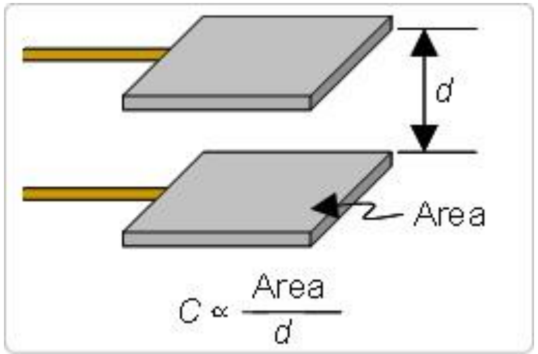
Capacitive Sensors

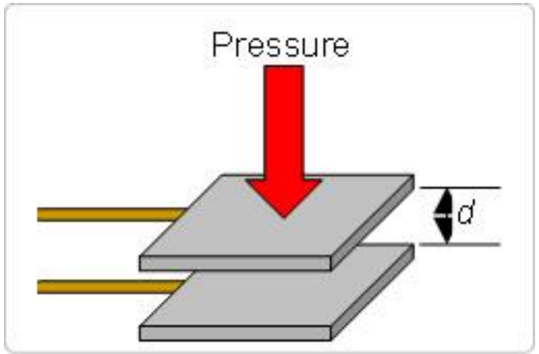


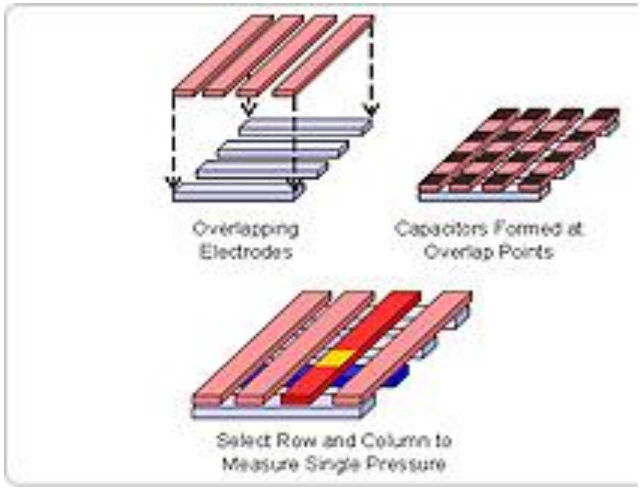
Capacity varies with the distance between the plates and the common area.
Both effects are used in sensors.

There are three ways to change the capacity: variation of the distance between the plates (d), variation of the shared area of the plates (A) and the variation of the dielectric constant (K).

PPS Capacitive Pressure Sensors







(Figures from Pressure Profile Systems)

- Capacitance is a measure of the electrical charge stored between two electrodes separated by an air gap.
- As the electrodes are moved closer to or farther from one another, the air gap changes, and therefore so does the capacitance.
- The simplicity of a capacitor allows for a great deal of flexibility in design and construction, and results are more repeatable and less likely to degrade over time.

Methods and Apparatus for Data Input (filed:1992)

US005305017A

United States Patent [19]
Gerpheide

[11] **Patent Number:** **5,305,017**
[45] **Date of Patent:** **Apr. 19, 1994**

[54] **METHODS AND APPARATUS FOR DATA INPUT**

[76] Inventor: **George E. Gerpheide,** 3481 S. Monte Verde Dr., Salt Lake City, Utah 84109

[21] Appl. No.: **914,043**

[22] Filed: **Jul. 13, 1992**

Related U.S. Application Data

[63] Continuation of Ser. No. 754,329, Sep. 4, 1991, which is a continuation of Ser. No. 394,566, Aug. 16, 1989.

[51] **Int. Cl.**[5] **G09G 3/02**
[52] **U.S. Cl.** **345/174;** 345/168
[58] **Field of Search** 340/706, 709, 710, 712; 341/20, 23; 178/18, 19; 345/173, 174, 168

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Primary Examiner—Ulysses Weldon
Assistant Examiner—M. Fatahiyar
Attorney, Agent, or Firm—Thorpe North & Western

[57] **ABSTRACT**

Methods and apparatus for data input. Devices are provided in accordance with this invention which utilize capacitive coupling of an object to the device to sense the object's position. The devices are comprised of a plurality of electrode strips which form virtual electrodes. The virtual electrodes are selectively connected to form virtual dipole electrodes which are responsive to the object's position.

17 Claims, 13 Drawing Sheets

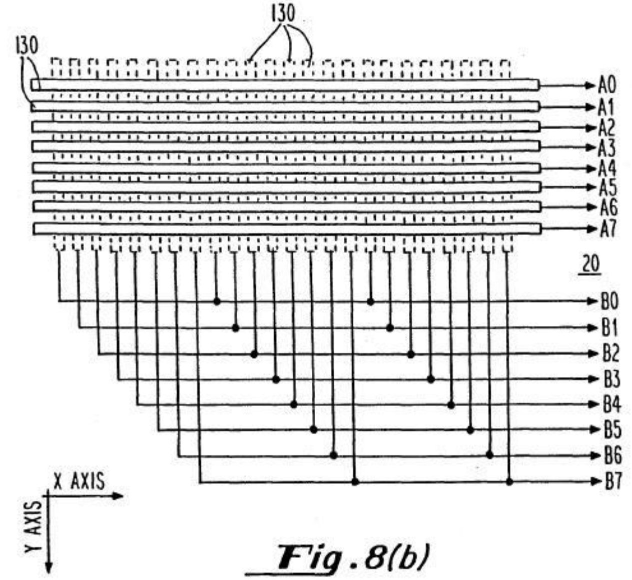
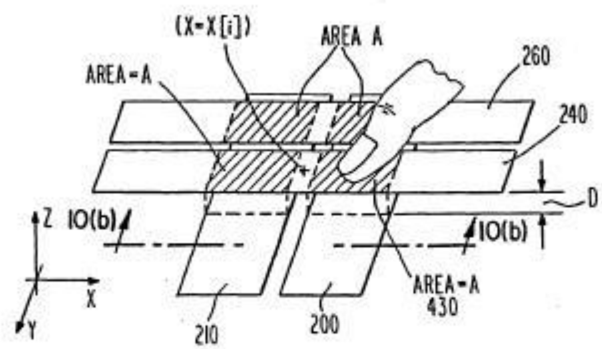
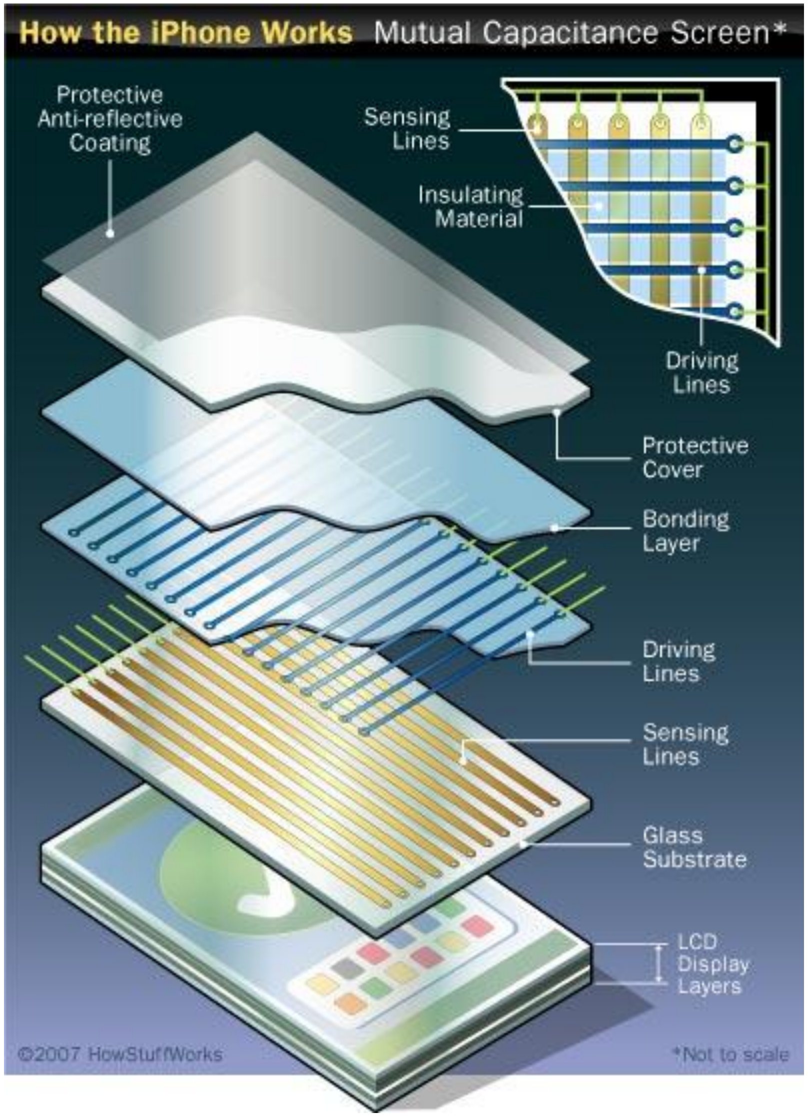


Fig.8(b)




How the iPhone Works Mutual Capacitance Screen*
Protective Anti-reflective Coating
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Insulating Material
Driving Lines
Protective Cover
Bonding Layer
Driving Lines
Sensing Lines
Glass Substrate
LCD Display Layers
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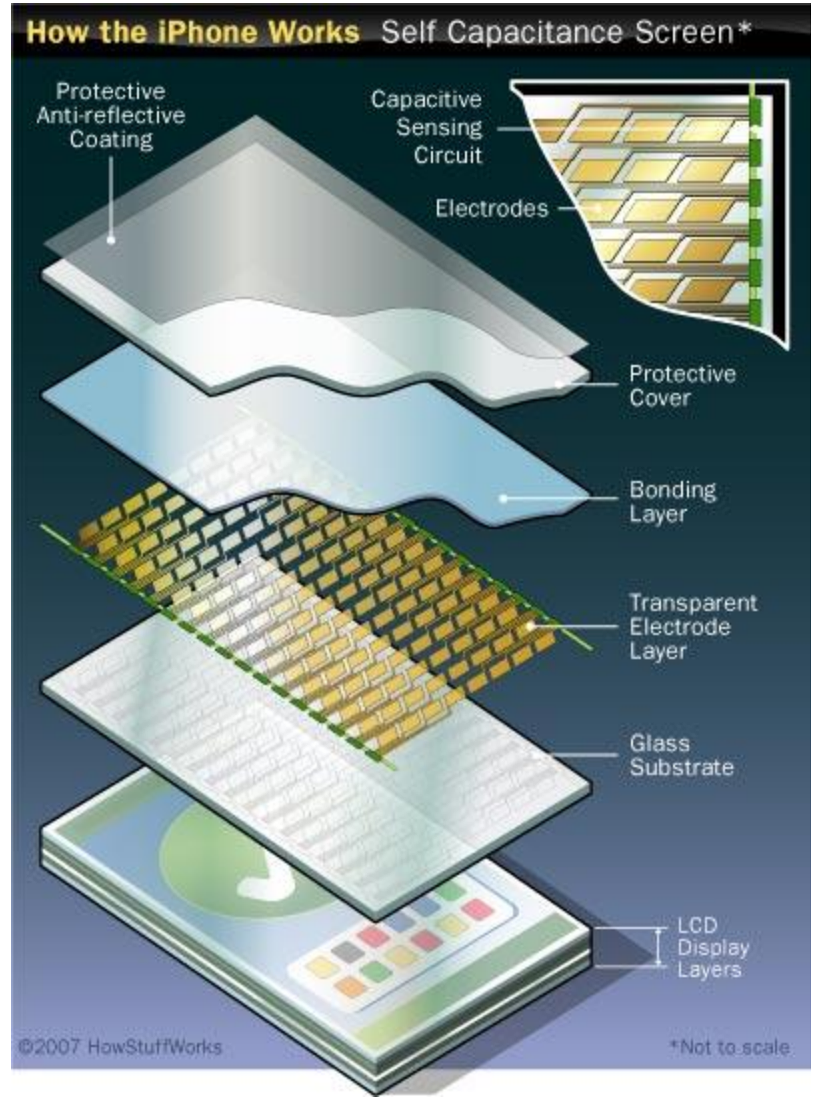
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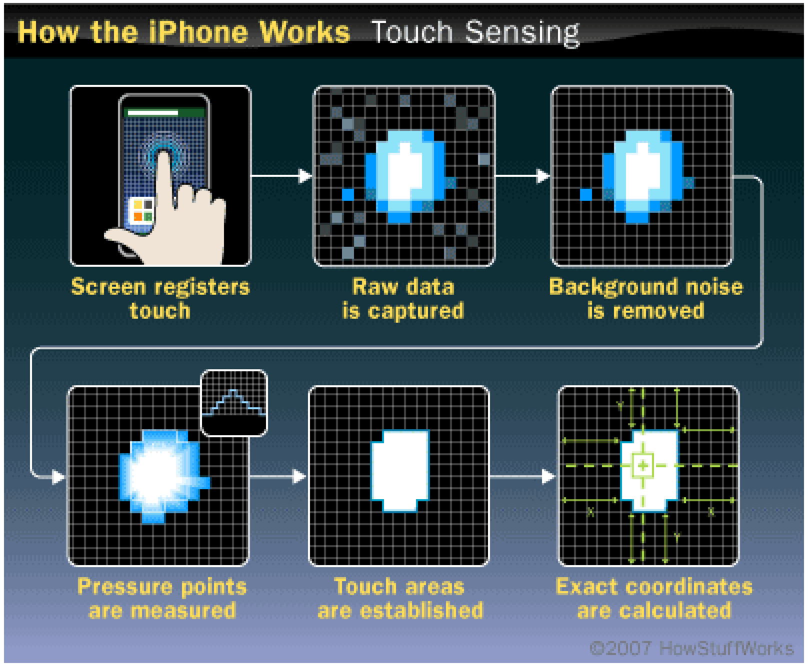
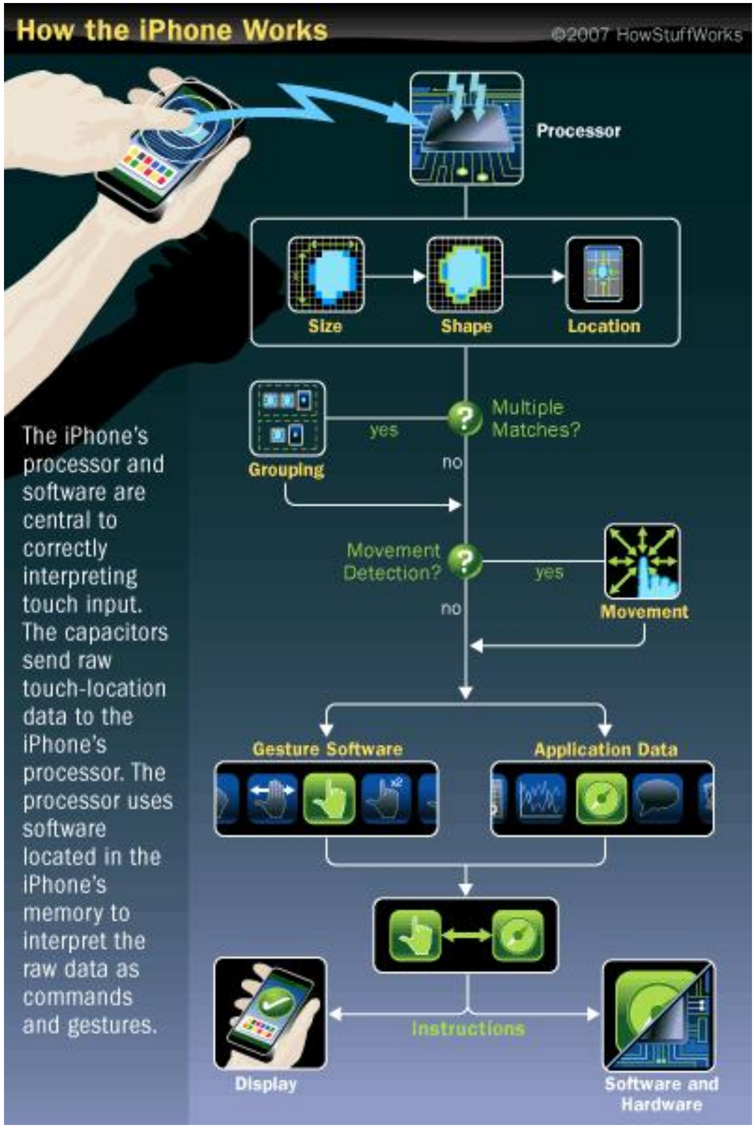

How the iPhone Works Touch Sensing
Screen registers touch
Raw data is captured
Background noise is removed
Pressure points are measured
Touch areas are established
Exact coordinates are calculated
©2007 HowStuffWorks


How the iPhone Works
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Processor
Size
Shape
Location
Grouping
yes
Multiple Matches?
no
Movement Detection?
yes
Movement
no
Gesture Software
Application Data
Display
Instructions
Software and Hardware
The iPhone's processor and software are central to correctly interpreting touch input. The capacitors send raw touch-location data to the iPhone's processor. The processor uses software located in the iPhone's memory to interpret the raw data as commands and gestures.

Case Study: Handshake Experiment

In the social interactions in many cultures, to touch and be touched is inevitable.

- ✓ Functionality
- ✓ Controls
- ✓ Cosmetic Appearance
- ✓ <u>Humanlike feel and warmth when touched</u>

Prosthetic devices should allow the user to pass unnoticed.

Handshake Experiment - Objectives

- To determine area of high contact during handshake
- To determine typical range of force in contacting area
- To provide benchmark data to duplicate with synthetic skins that will help us to design prosthetic/sociable robotic skins with characteristics similar to that of human hand

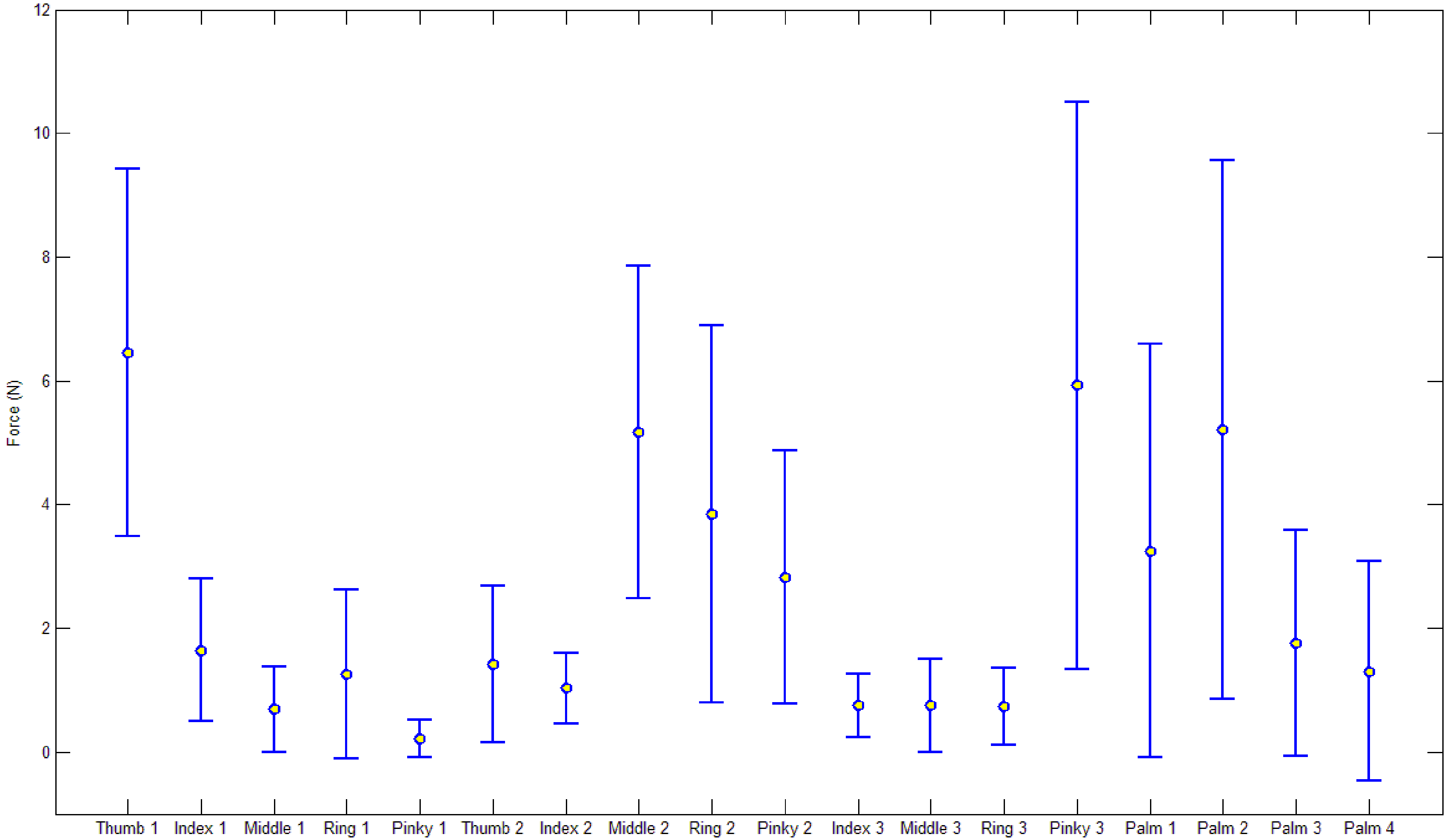
Handshake Experiments

- Where are the high contact areas?
- What is the dispersion/range of forces involved?

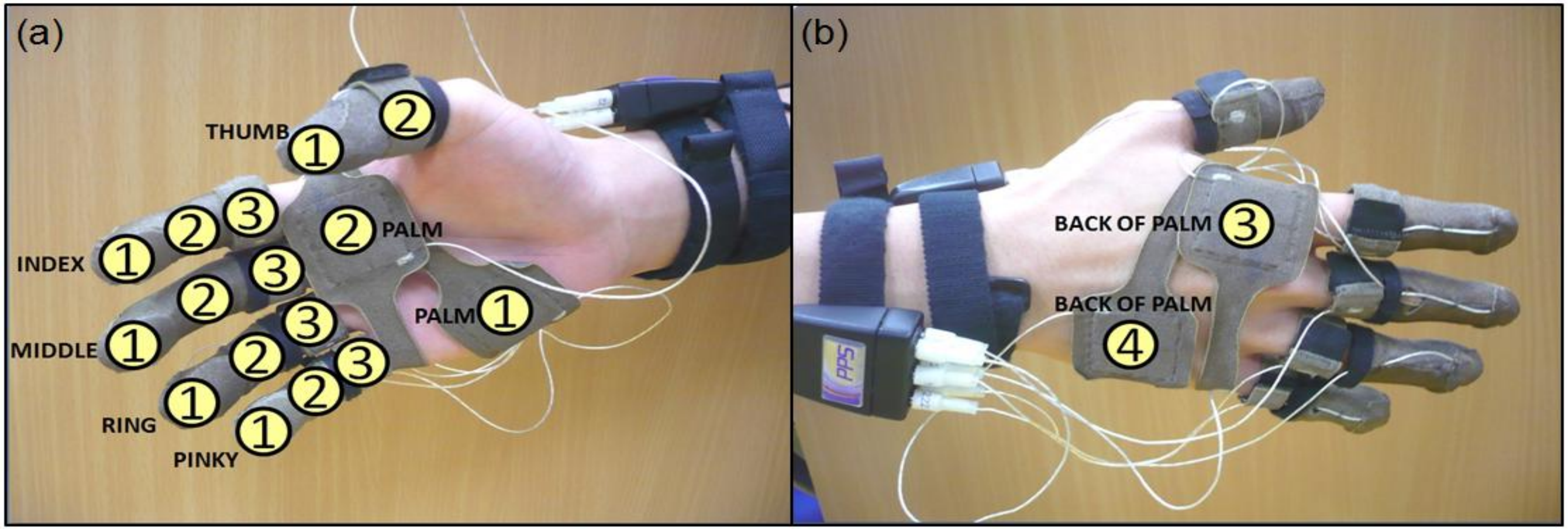
- Coders: male
- Subjects: Coder shake hands with 30 male students each.
- The coder were trained to give a neutral handshake and wait for the handshake partner to initiate.
- Handshake partner was instructed to give their normal handshake.

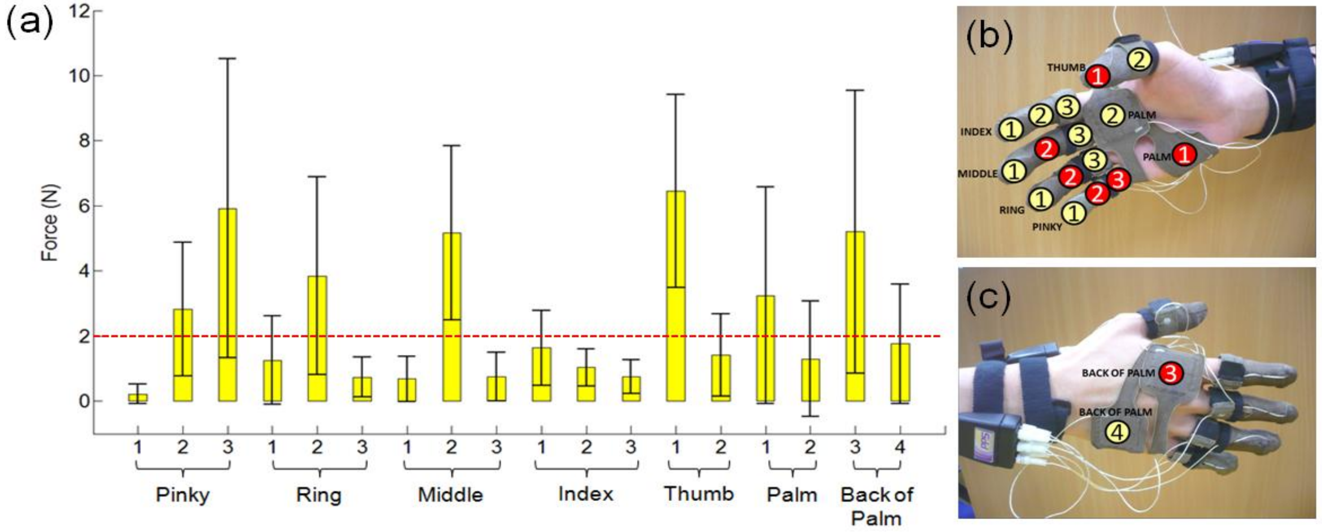
Subjects' Data	Mean	Std Dev	Min	Max
Age	**25.8780**	**2.9765**	**22**	**34**
Height (cm)	**173.2439**	**4.5923**	**163**	**183**
Weight (kg)	**66.1463**	**10.3503**	**50**	**105**
Hand Length (mm)	**187.3111**	**10.1395**	**160**	**220**
Hand Width (mm)	**88.4889**	**7.0279**	**65**	**108**

Handshake Experiment – Range of Forces

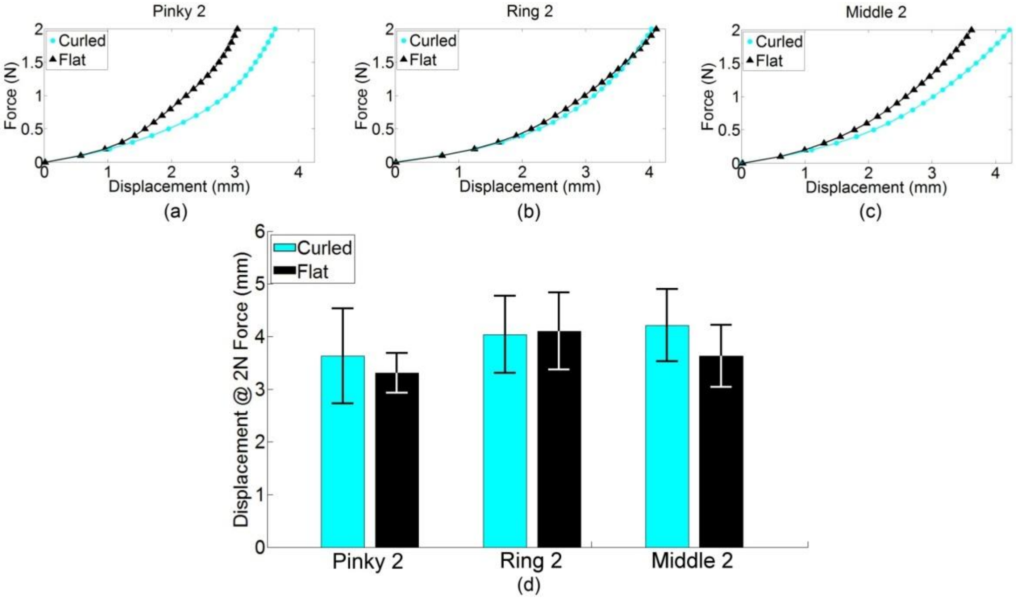


Lifelike Soft Synthetic Skins - Experiments





Lifelike Soft Synthetic Skins - Experiments



Making Realistic Skin for Robots

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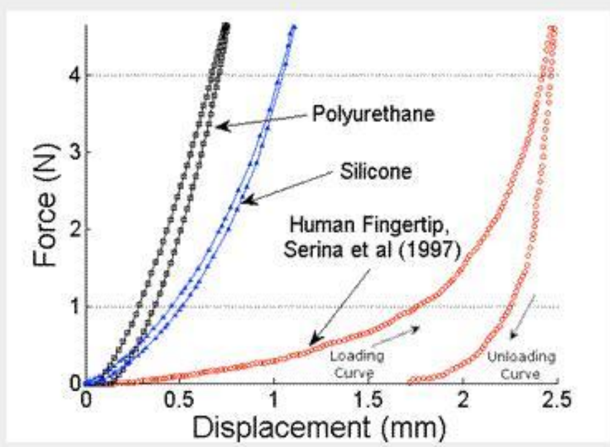
Wednesday, September 23, 2009

Making Realistic Skin for Robots

Without realistic synthetic skin, robots will never be entirely accepted socially. Yet even measuring what it means for skin to be humanlike is proving tough.



When it comes to building realistic robots, it's not just the way they look that's important. It's also the way they feel to the touch, says John-John Cabibihan at the National University of Singapore and pals. They argue that if robots are ever to be

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Artificial skin can't fool the human touch

- 08 October 2009
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ARTIFICIAL skin covering prosthetics and humanoid robots might look like the real thing, but grasp an artificial hand in yours and the difference is apparent.

Fake skin responds very differently to being touched, discovered John-John Cabibihan at the National University of Singapore and colleagues from Italy, Norway and France (www.arxiv.org/abs/0909.3559).

They subjected silicone or polyurethane fingertips to a battery of physical tests to explore how they stretch, deform and spring back into shape when compared to real fingertips. The tests involved tapping the fingertip on a surface, and deforming it with a probe.

Results showed that the two artificial materials, like real skin, can deform to closely match an outside force. The difference is that much more force is needed to achieve the same effect.

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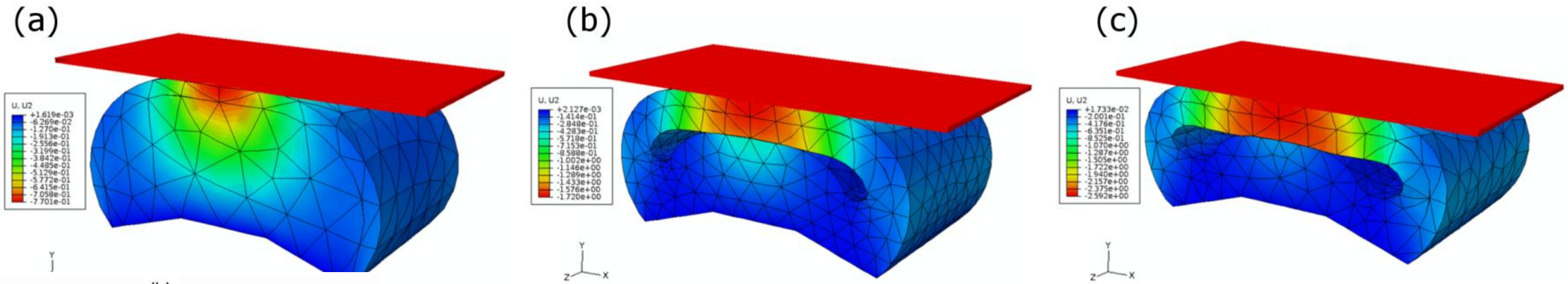
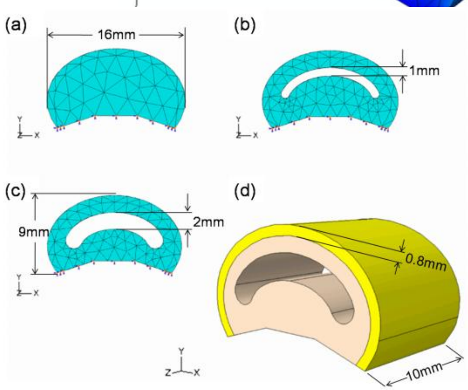
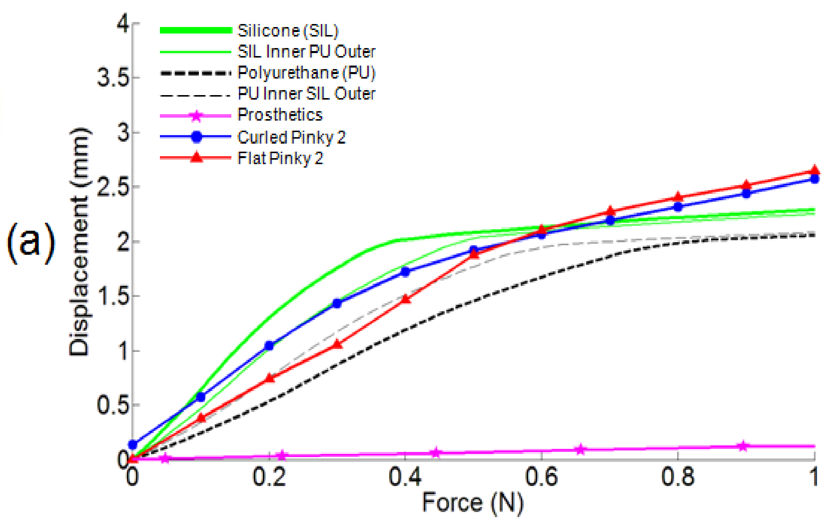
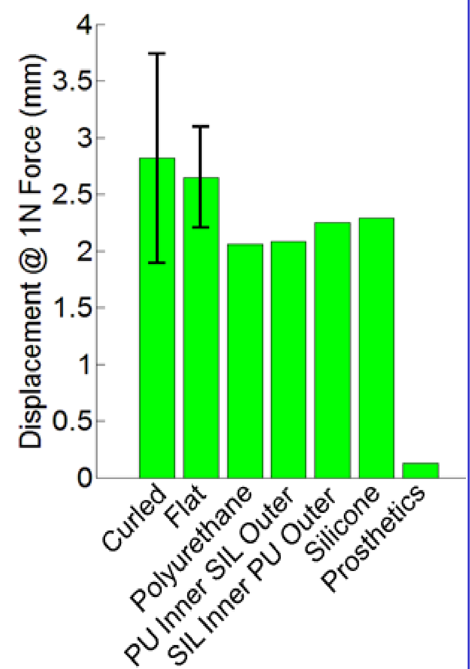
18 September 2010

Lifelike Soft Synthetic Skins - Experiments









CyberGlove II

- 22 high-accuracy joint-angle measurements
- Resistive bend-sensing technology
- Transform hand and finger motions into real-time digital joint-angle data

CyberGlove Resistive Bend-Sensing Technology

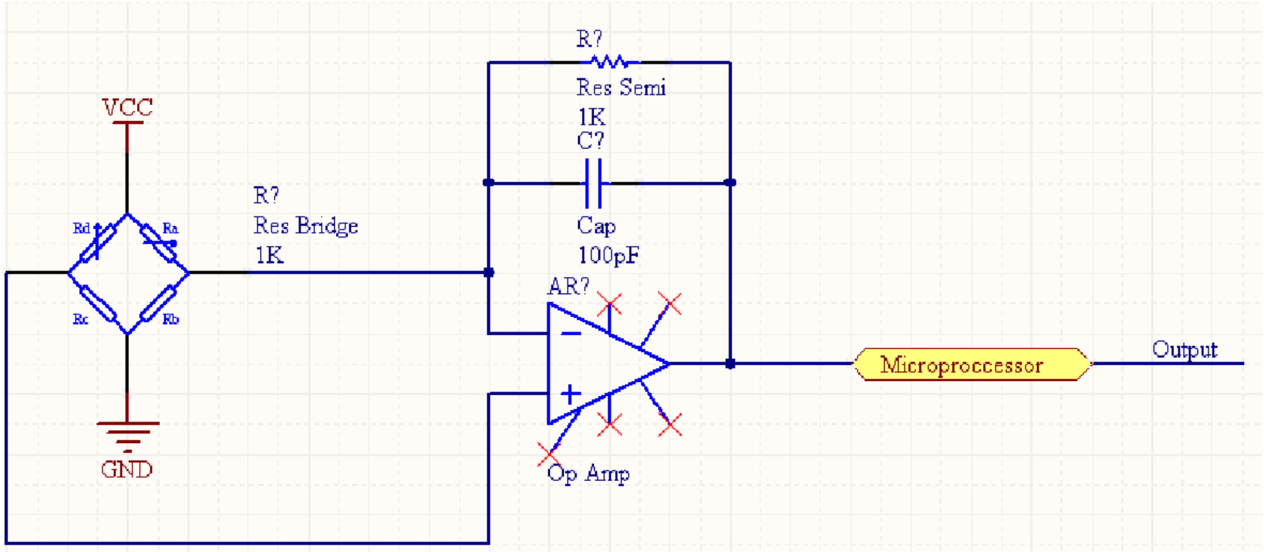


Figure 1: Simplified model circuit of resistive bend sensing

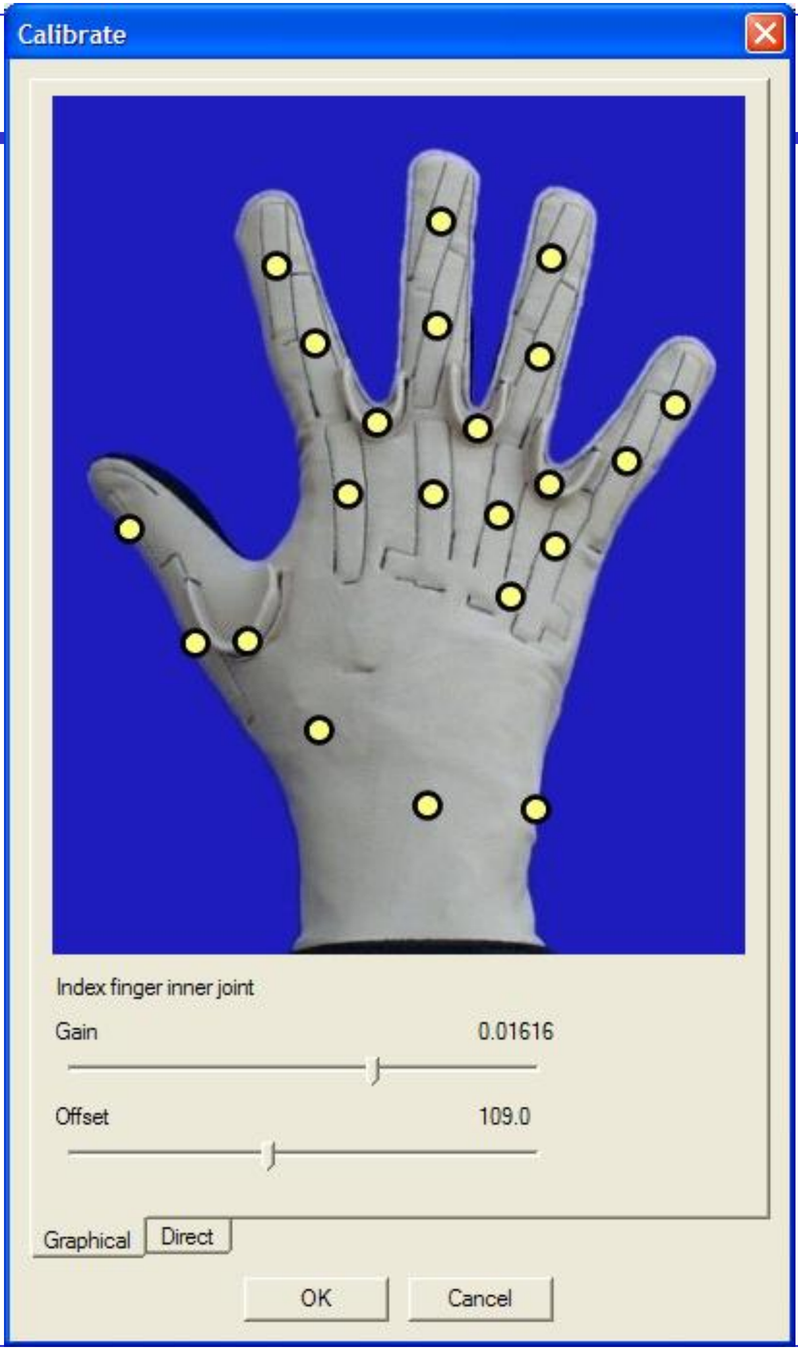
Change in joint angles are detected when the movement of the hand cause a change in length of the material

-> cause a change in the resistance of the material

-> leads to a change in voltage

-> change in voltage is amplified by an amplifier and filtered from unwanted noises

-> serves as an output to the microprocessor to be processed



Sensor Locations

3 flexion sensors per finger

4 abduction sensors

1 palm-arch sensor

2 flexion and abduction sensors

Technical Specifications

Number of sensors: 22

Sensor Resolution: 0.5 degrees

Sensor Repeatability: 1 degree

Sensor Linearity: 0.6%

Sensor Data Rate: 90 records/sec minimum

Operating Range: 30 ft radius from USB

Case: Biomechanics Characterization of Handshake

Processing

Perform gestures (i.e. handshake)

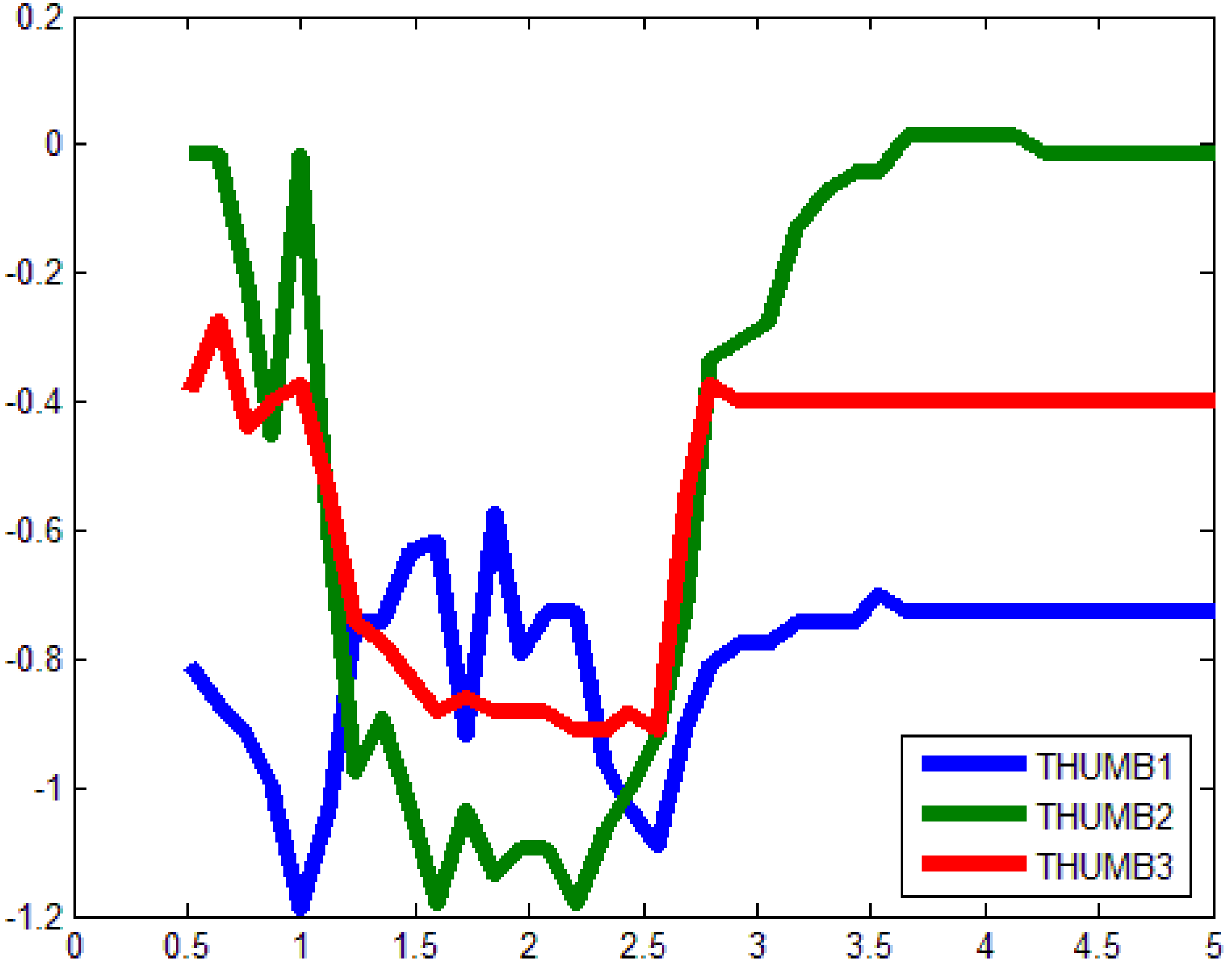
Time	Thumb1	Thumb2	Thumb3	Index1	Index2	Index3	Middle1	Middle2	Middle3
0.5160	-0.8078	-0.0146	-0.3853	-0.3232	-0.3939	0.0678	-0.1380	-0.3247	0.2207
0.6410	-0.8712	-0.0146	-0.2711	-0.0970	-0.2480	0.0979	0.0690	-0.1443	0.2628
0.7660	-0.9187	-0.2189	-0.4424	-0.0323	-0.1313	0.1280	0.1035	0.0361	0.2838
0.8750	-0.9979	-0.4523	-0.3996	-0.2101	-0.1897	0.1280	0.0518	-0.0722	0.2207
1.0000	-1.1880	-0.0146	-0.3710	-0.0970	-0.2189	0.0904	0.1035	-0.4149	0.0631
1.1250	-1.0296	-0.6128	-0.5423	-0.6141	-0.4669	-0.1657	-0.3623	-0.9381	-0.3048
1.2340	-0.7445	-0.9775	-0.7420	-0.7272	-0.7441	-0.6024	-0.5348	-1.0463	-0.4730
1.3590	-0.7445	-0.8900	-0.7706	-0.6302	-0.7733	-0.6024	-0.5003	-1.0463	-0.4519
1.4840	-0.6336	-1.0359	-0.8277	-0.5656	-0.8025	-0.6401	-0.3968	-1.0824	-0.4519
1.5940	-0.6178	-1.1818	-0.8847	-0.5656	-0.8608	-0.7078	-0.3623	-1.1185	-0.4940
1.7190	-0.9187	-1.0359	-0.8562	-0.5656	-0.8316	-0.6250	-0.4313	-1.1185	-0.4519
1.8440	-0.5702	-1.1380	-0.8847	-0.5333	-0.8900	-0.7078	-0.3278	-1.1546	-0.4730
1.9690	-0.7920	-1.0943	-0.8847	-0.5333	-0.8900	-0.7078	-0.3623	-1.1546	-0.4730
2.0780	-0.7286	-1.0943	-0.8847	-0.5333	-0.8900	-0.7078	-0.3623	-1.1546	-0.4519
2.2030	-0.7286	-1.1818	-0.9133	-0.5333	-0.9192	-0.7530	-0.3623	-1.1546	-0.4940
2.3280	-0.9662	-1.0651	-0.9133	-0.5010	-0.9192	-0.7229	-0.4313	-1.1546	-0.4940
2.4380	-1.0296	-1.0067	-0.8847	-0.4686	-0.9192	-0.6928	-0.3968	-1.1906	-0.4940
2.5630	-1.0930	-0.9192	-0.9133	-0.4686	-0.9192	-0.6250	-0.3968	-1.1546	-0.5360

Captured data

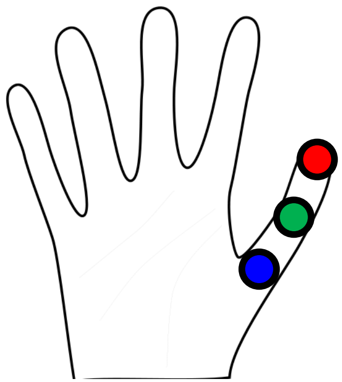
Sample of Characterization Results

Time	Thumb1	Thumb2	Thumb3	Index1	Index2	Index3	Middle1	Middle2	Middle3
0.5160	-0.8078	-0.0146	-0.3853	-0.3232	-0.3939	0.0678	-0.1380	-0.3247	0.2207
0.6410	-0.8712	-0.0146	-0.2711	-0.0970	-0.2480	0.0979	0.0690	-0.1443	0.2628
0.7660	-0.9187	-0.2189	-0.4424	-0.0323	-0.1313	0.1280	0.1035	0.0361	0.2838
0.8750	-0.9979	-0.4523	-0.3996	-0.2101	-0.1897	0.1280	0.0518	-0.0722	0.2207
1.0000	-1.1880	-0.0146	-0.3710	-0.0970	-0.2189	0.0904	0.1035	-0.4149	0.0631
1.1250	-1.0296	-0.6128	-0.5423	-0.6141	-0.4669	-0.1657	-0.3623	-0.9381	-0.3048
1.2340	-0.7445	-0.9775	-0.7420	-0.7272	-0.7441	-0.6024	-0.5348	-1.0463	-0.4730
1.3590	-0.7445	-0.8900	-0.7706	-0.6302	-0.7733	-0.6024	-0.5003	-1.0463	-0.4519
1.4840	-0.6336	-1.0359	-0.8277	-0.5656	-0.8025	-0.6401	-0.3968	-1.0824	-0.4519
1.5940	-0.6178	-1.1818	-0.8847	-0.5656	-0.8608	-0.7078	-0.3623	-1.1185	-0.4940
1.7190	-0.9187	-1.0359	-0.8562	-0.5656	-0.8316	-0.6250	-0.4313	-1.1185	-0.4519
1.8440	-0.5702	-1.1380	-0.8847	-0.5333	-0.8900	-0.7078	-0.3278	-1.1546	-0.4730
1.9690	-0.7920	-1.0943	-0.8847	-0.5333	-0.8900	-0.7078	-0.3623	-1.1546	-0.4730
2.0780	-0.7286	-1.0943	-0.8847	-0.5333	-0.8900	-0.7078	-0.3623	-1.1546	-0.4519
2.2030	-0.7286	-1.1818	-0.9133	-0.5333	-0.9192	-0.7530	-0.3623	-1.1546	-0.4940
2.3280	-0.9662	-1.0651	-0.9133	-0.5010	-0.9192	-0.7229	-0.4313	-1.1546	-0.4940
2.4380	-1.0296	-1.0067	-0.8847	-0.4686	-0.9192	-0.6928	-0.3968	-1.1906	-0.4940
2.5630	-1.0930	-0.9192	-0.9133	-0.4686	-0.9192	-0.6250	-0.3968	-1.1546	-0.5360

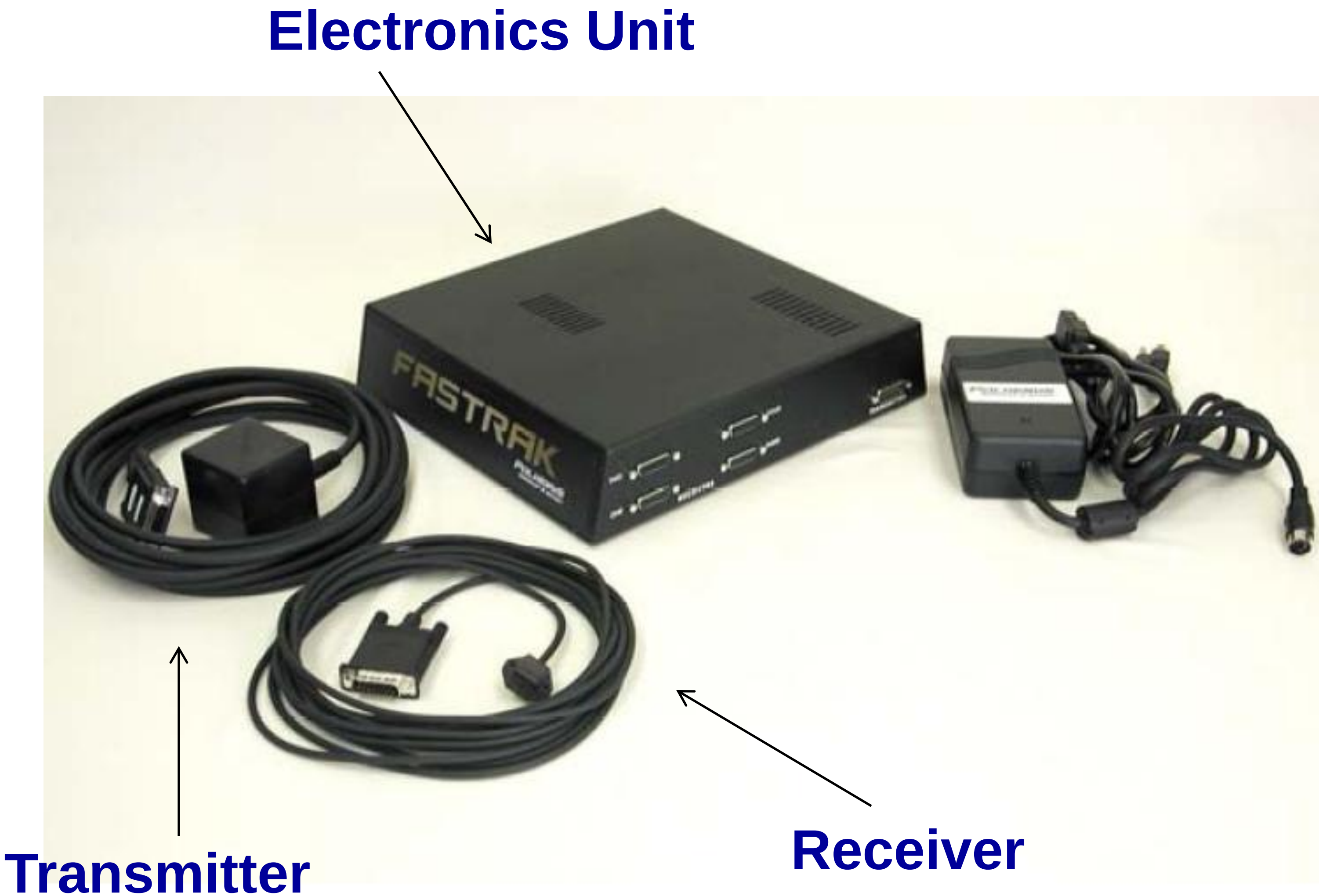
Sample of Characterization Results



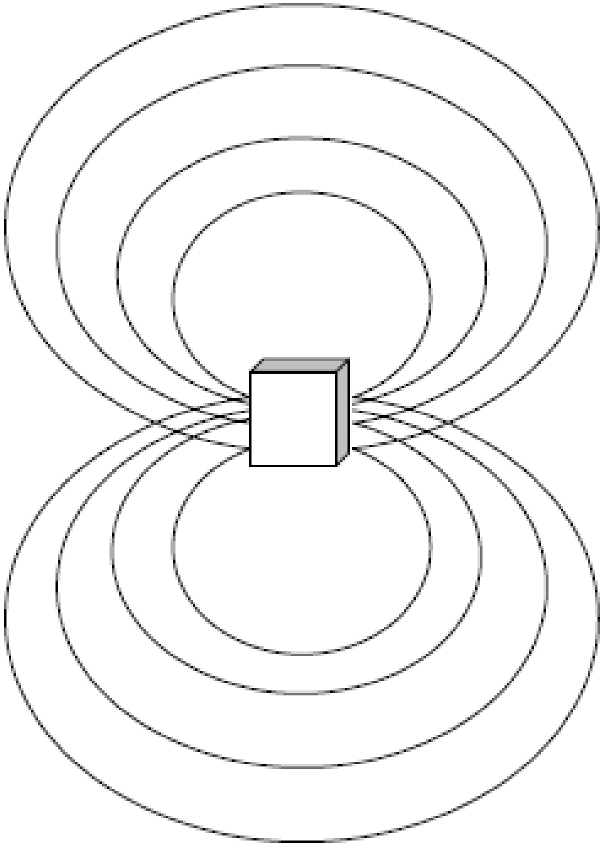
Joint Angles



Polhemus Motion Tracking System



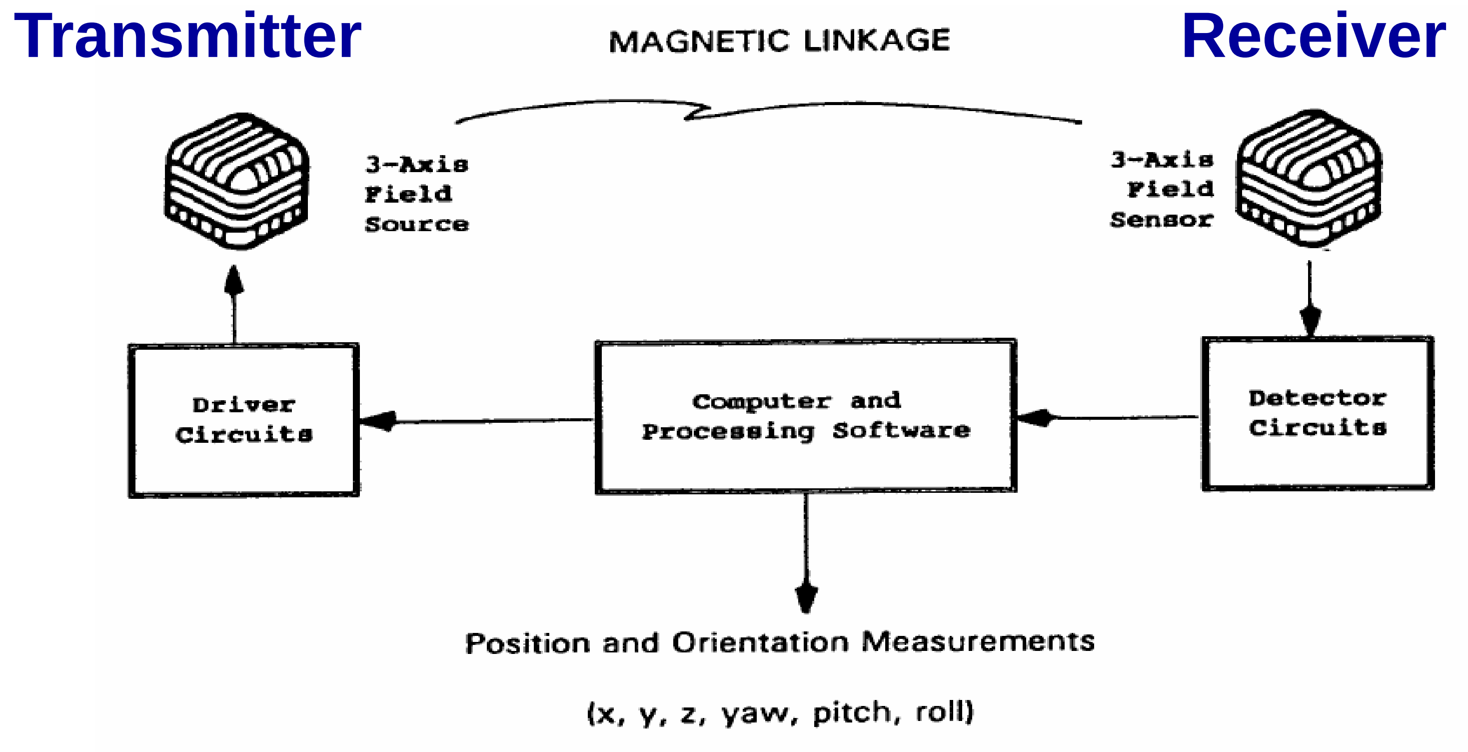
Motion Sensing Technology



Magnetic dipole

The transmitter uses an AC magnetic tracker technology (magnetic dipole) to detect motion

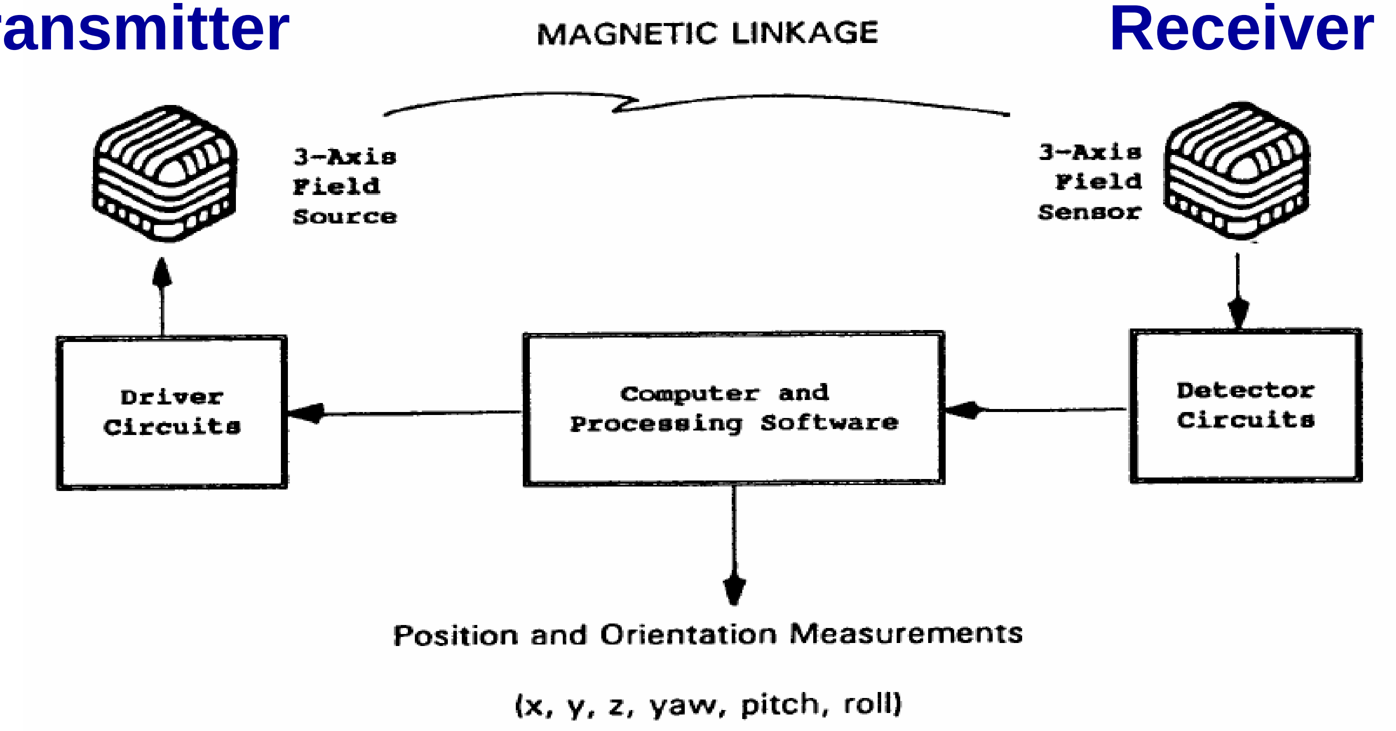
Motion Sensing Technology



The transmitter is an antenna which transmits a magnetic dipole from a fixed position. The receiver is a movable antenna which receives the magnetic dipole.

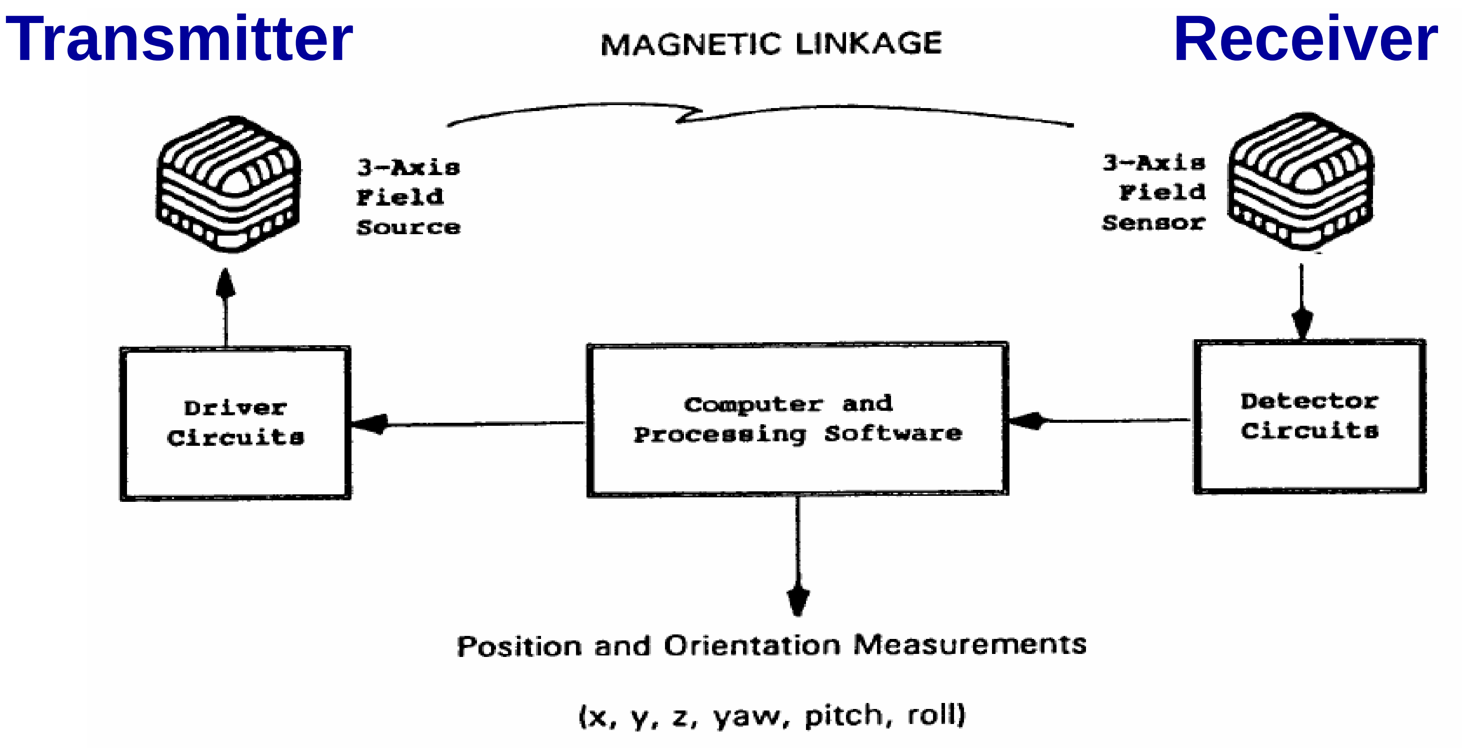
Motion Sensing Technology

Transmitter **Receiver**



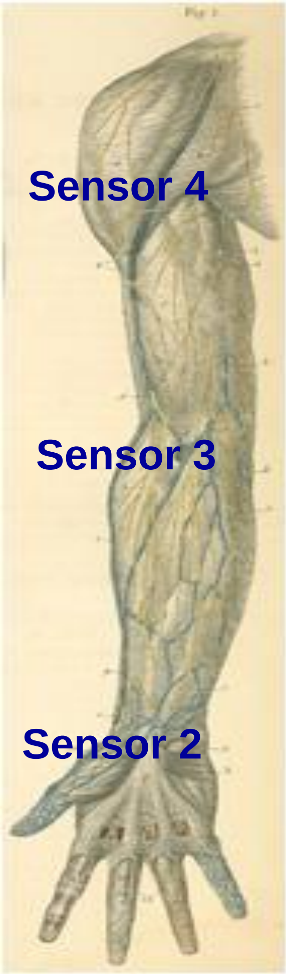
The receiver and transmitter antenna each consist of 3 mutually orthogonal loops (coils). The 3 loops of the receiver antenna are excited by the 3 magnetic dipoles generated by the transmitter.

Motion Sensing Technology



Through the excitation of the 3 loops at the receiver, 3 independent vector output are obtained and used to measure the position and orientation of the object.

Case: Detection of waving motion



Coordinates obtained for sensor 2

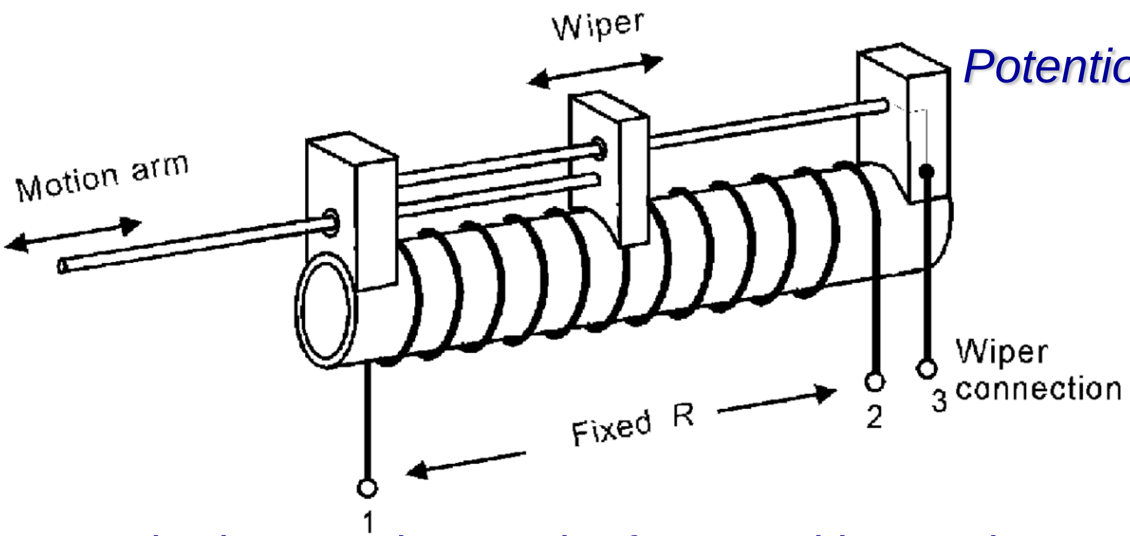
Time	X	Y	Z
0	24.68	18.77	26.73
0.025	24.69	18.75	26.72
0.05	24.68	18.78	26.7
0.075	24.65	18.78	26.7
0.1	24.55	18.87	26.68
0.125	24.36	18.96	26.72
0.15	24.1	19.1	26.67
0.175	23.5	19.32	26.95
0.2	23.11	19.74	26.89
0.225	22.57	20.38	26.85
0.25	21.94	21.22	26.79
0.275	21.48	22.07	26.78
0.3	21.22	23.18	26.54
0.325	21.37	24.24	26.39
0.35	21.98	25.2	26.21
0.375	22.67	25.89	26.66
0.4	23.68	26.55	27.03
0.425	25.21	26.85	27.21
0.45	26.8	26.83	27.49
0.475	28.38	26.4	27.93
0.5	30.18	25.76	28.01
0.525	31.69	24.78	28.07
0.55	32.6	24.15	27.94
0.575	33.06	23.43	27.83
0.6	32.81	23.42	27.81
0.625	32	23.91	27.92

- Data is sampled at 40 Hz, i.e. T= 0.025s
- The coordinates are measured from the position of the transmitter (reference frame)

Potentiometric Sensors

- The simplest type of displacement sensor involves the action of displacement in moving the wiper of a potentiometer.
- It converts linear or angular motion into a changing resistance that may be converted directly to voltage and/or current signals.
- Typical problems: mechanical wear, friction in the wiper action, limited resolution in the wire-wound units and high electronic noise.

Potentiometric Sensors



Potentiometric displacement sensor.

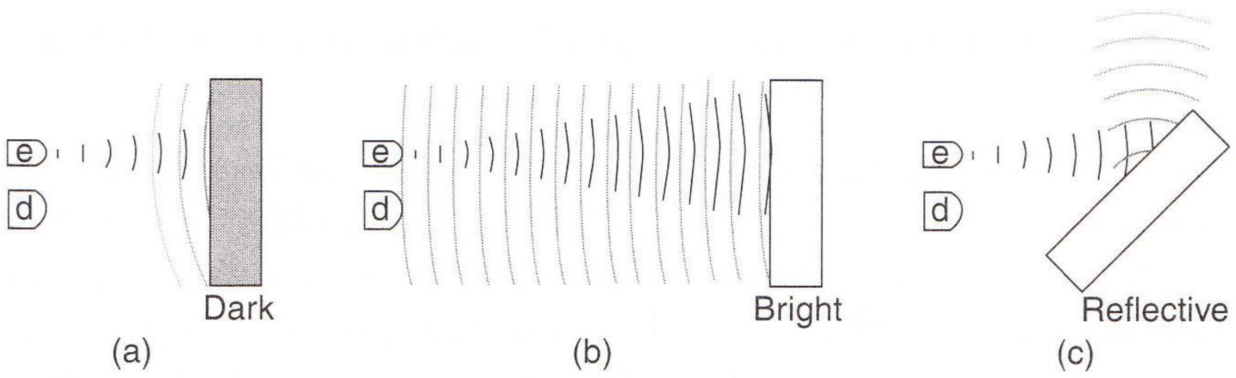
(The figure is highly pictorial. In actual sensors, the coil is very tightly wound of very fine wire).

- A wire is wound around a form, making a wire-wound resistor with fixed resistance, R, between its endpoints, 1 and 2.
- A wiper assembly is connected in such a way that motion of an arm causes the wiper to slide across the wire-wound turns of the fixed resistor.
- An electrical connection is made to this wiper. Therefore, as the arm moves back and forth, the resistance between the wiper connection, 3, and either fixed resistor connection will change in proportion to the motion.
- The potentiometric sensor is simply a three terminal variable resistor. The resolution of this sensor is limited to the distance, Δx, between individual turns of wire, with the resulting resistance change of the single turn.

Gypsy Motion Capture

http://www.youtube.com/watch?v=okq4EznnnEo&feature=related

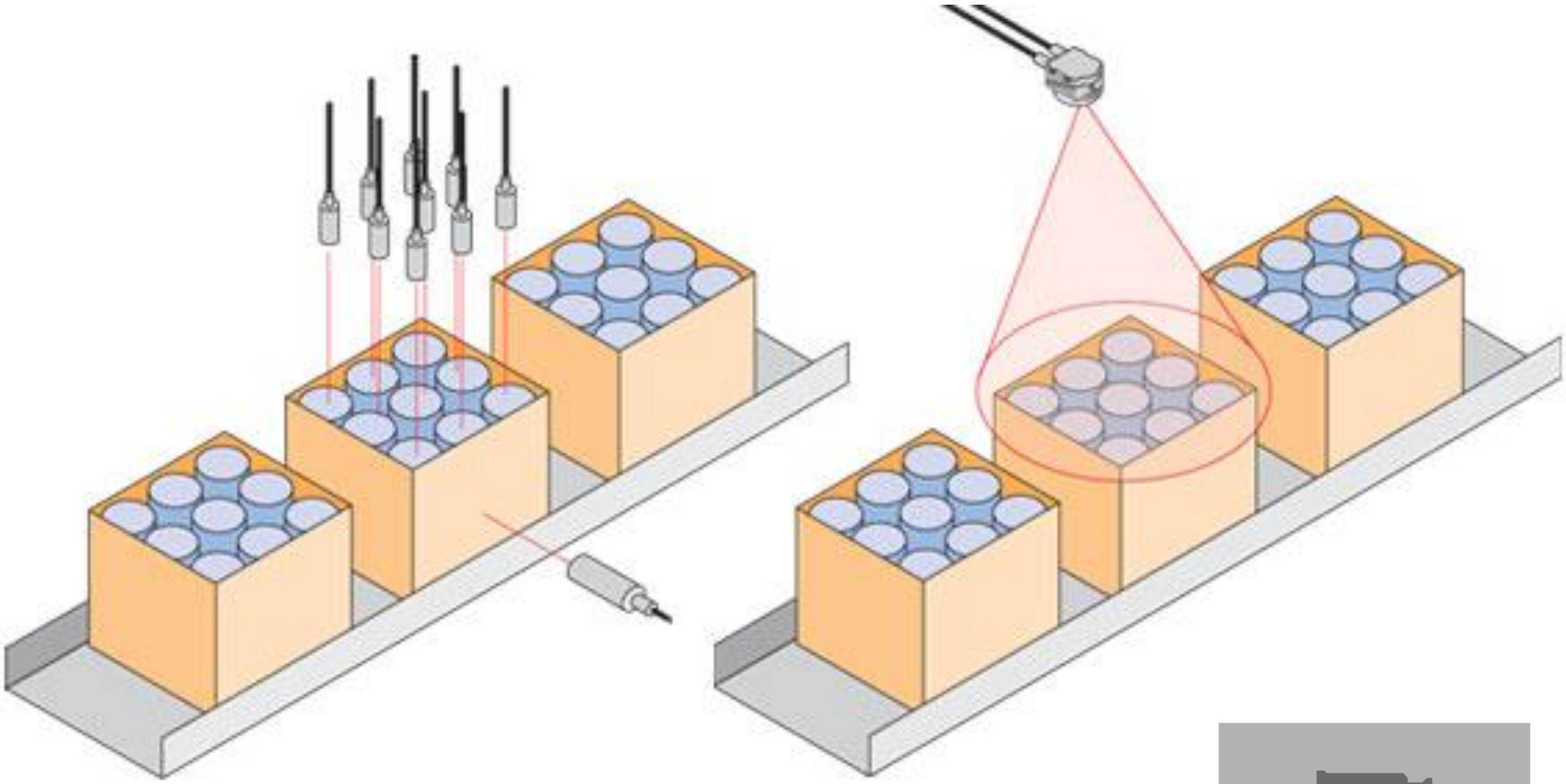
IR Sensors: "Is an object nearby?"



- The dividing line between what is considered nearby or far away depends strongly on the color and texture of the object surface.
- In (a), IR radiation from the emitter, e, strikes a dark, highly absorptive object. No signal returns to detector, d, and the sensor reports that no obstacle is present.
- In (b), the bright reflective object is detected despite the fact that it is more distant than the dark object in (a) that was not detected.
- In (c), a nearby reflective object in (a) that was not detected because the object directs most of the radiation away from the detector.

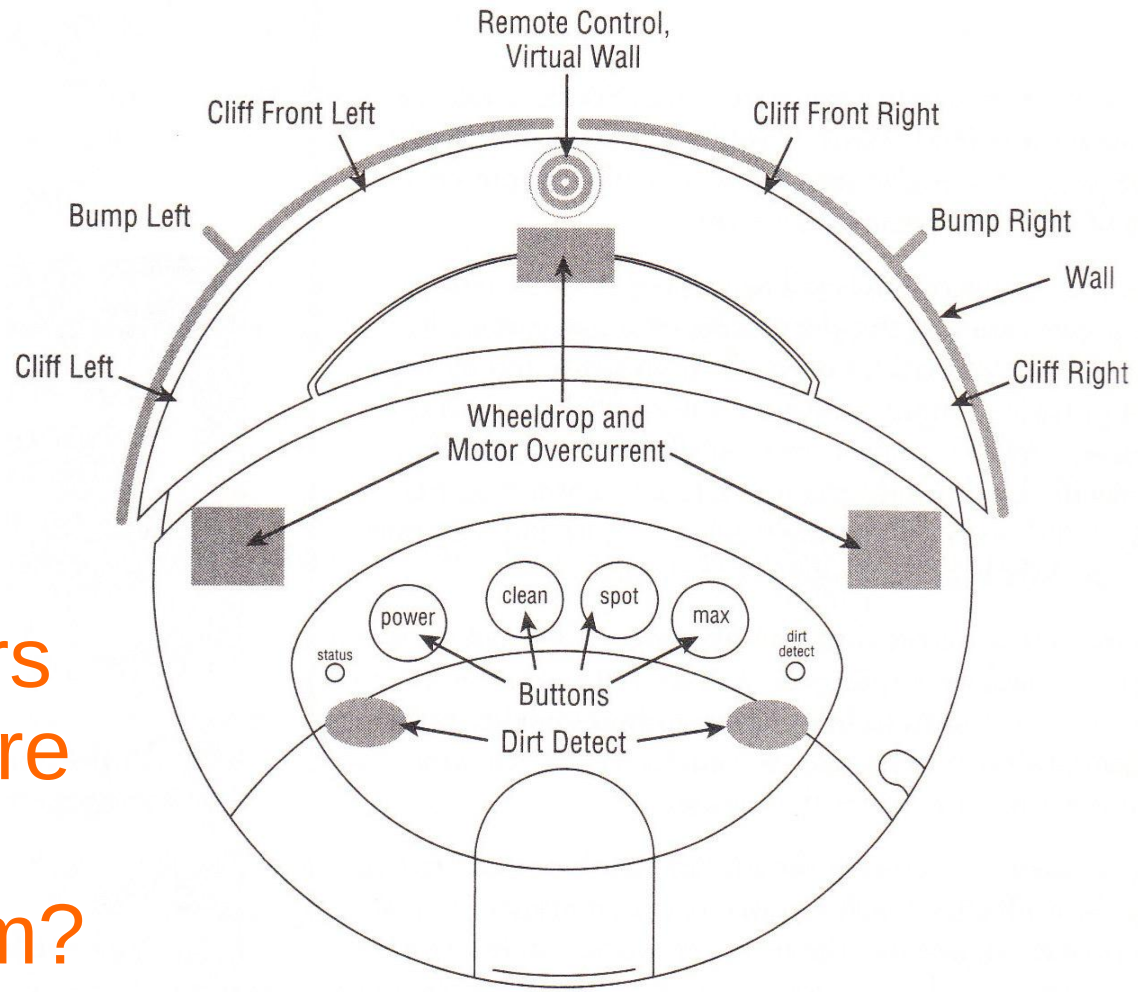
Source: Jones, Robot Programming, 2004

Industrial Optical Sensors



Source: http://www.balluff.com/Balluff/us/NewsChannel/Articles/en/2008-04_Vision-Article.htm

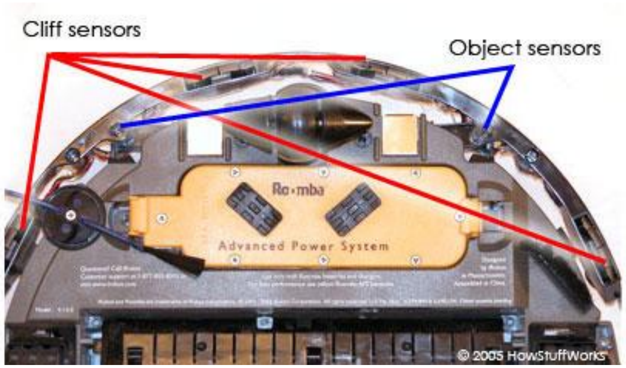
Deconstructing the iRobot Roomba

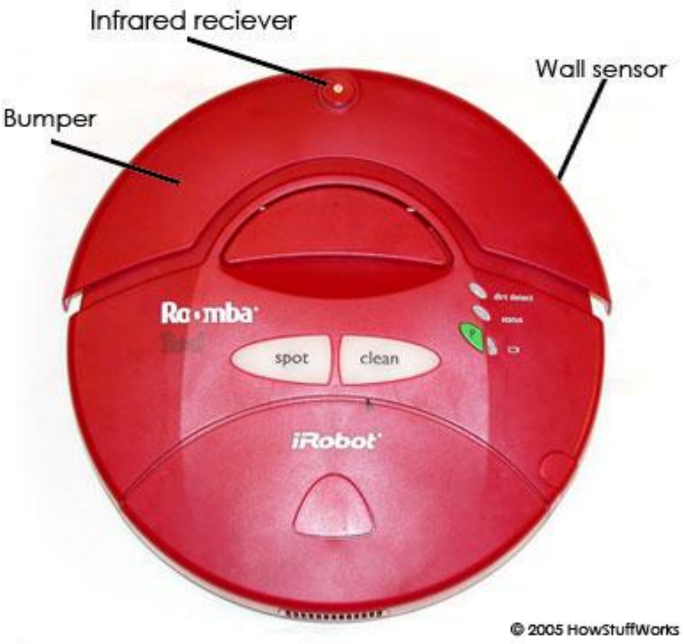


How many pairs of IR sensors are there in the Roomba System?

Source: Kurt, Hacking Roomba, 2007

Deconstructing the iRobot Roomba





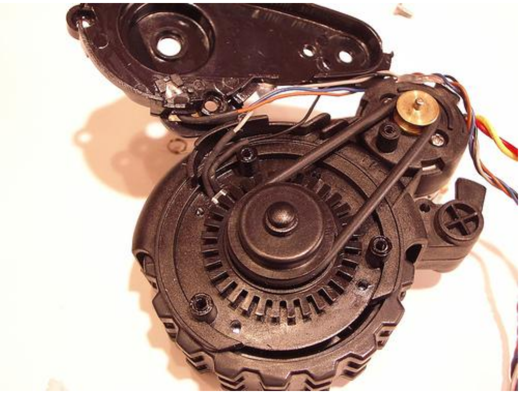
Cliff sensors (4)

Bump sensors or Object sensors (2)

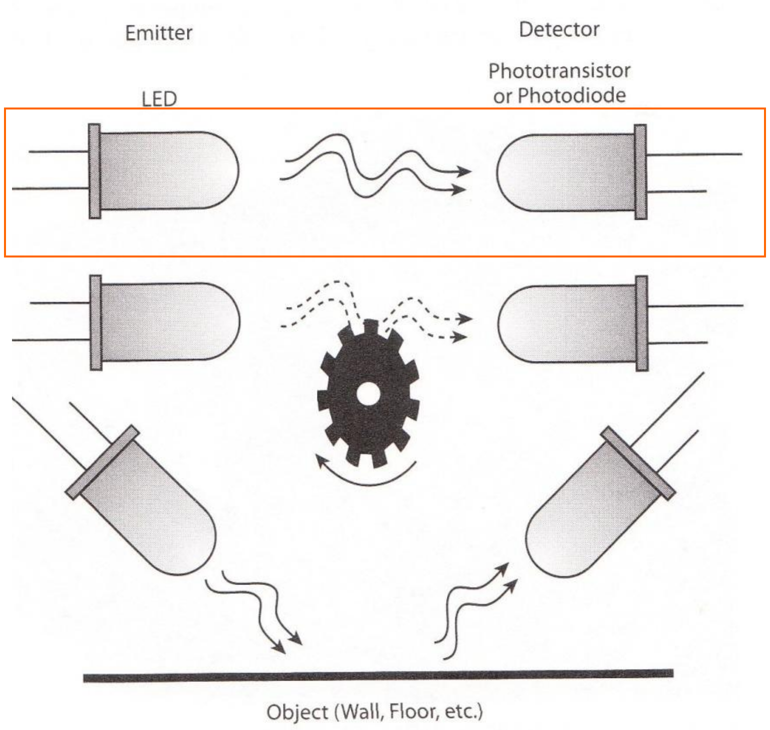
Wall following sensors (1)

Virtual wall sensors (1)

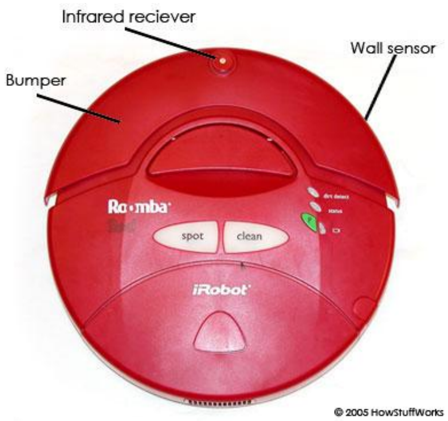
Optical encoders (2)

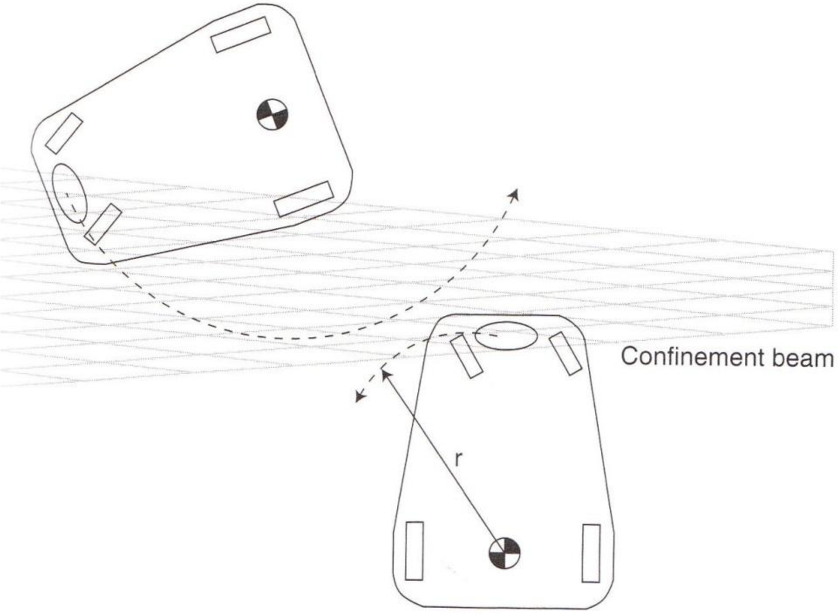


e/d Configuration for the Virtual Wall



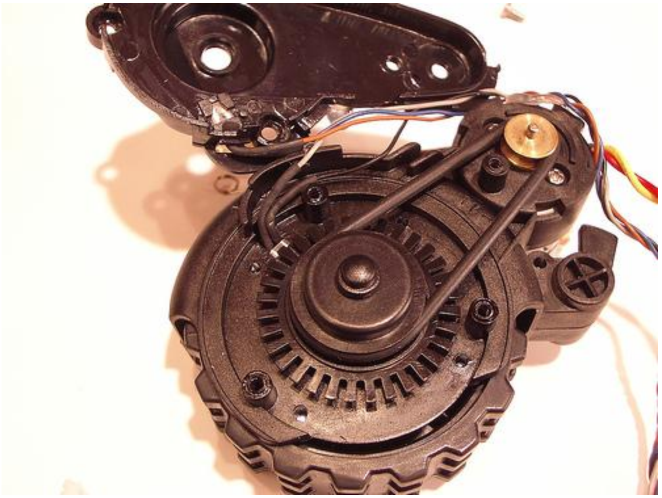
Source: Kurt, Hacking Roomba, 2007

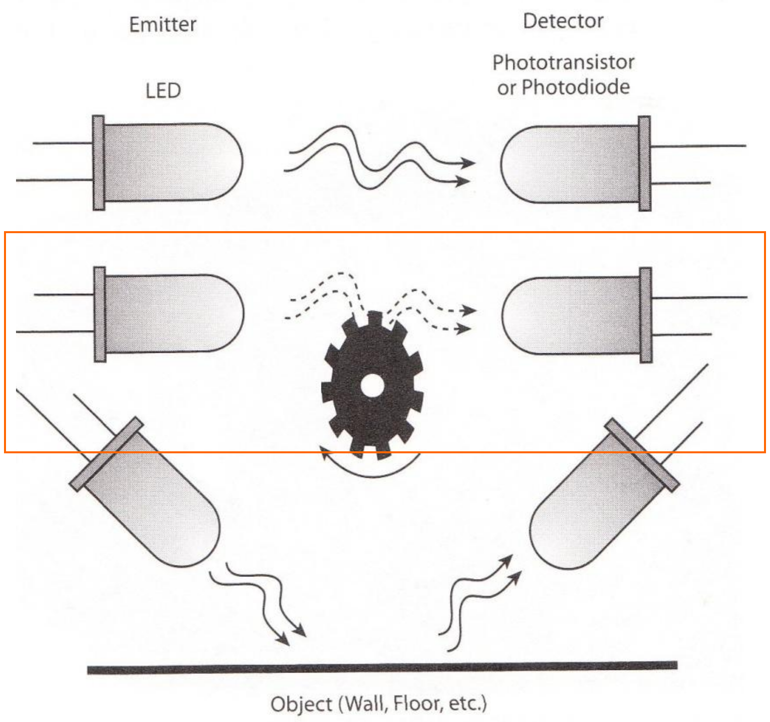




Source: Jones, Robot Programming, 2004

e/d Configuration for the Wheel Speed

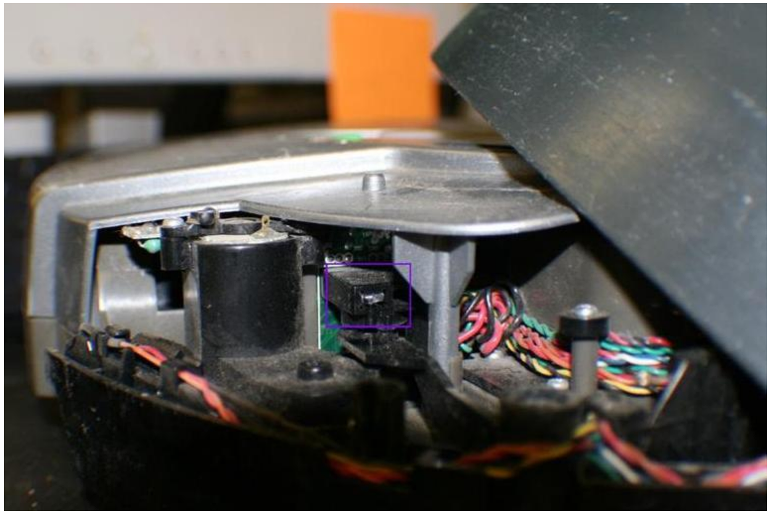


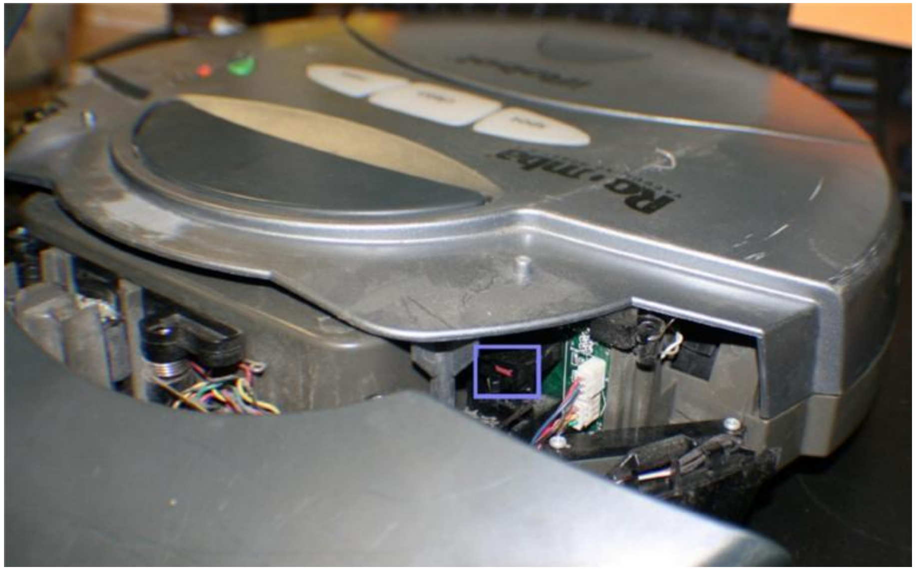


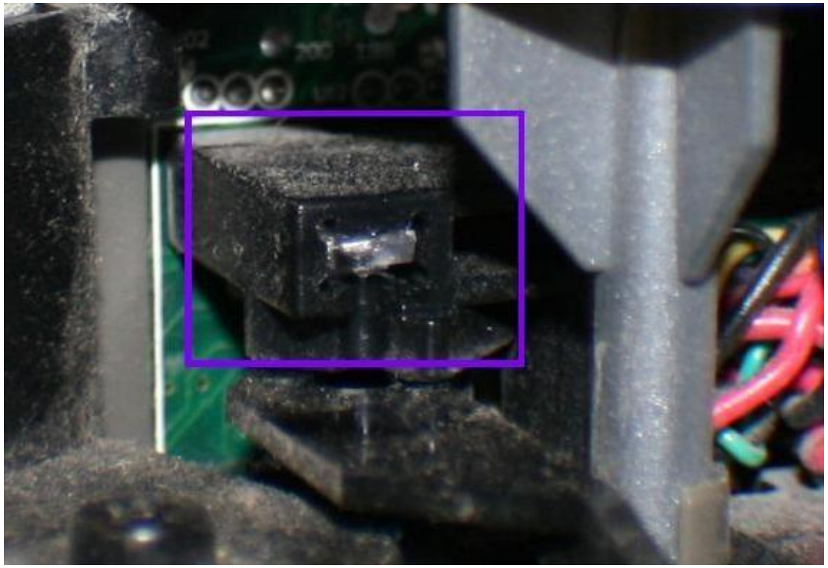
Source: Kurt, Hacking Roomba, 2007

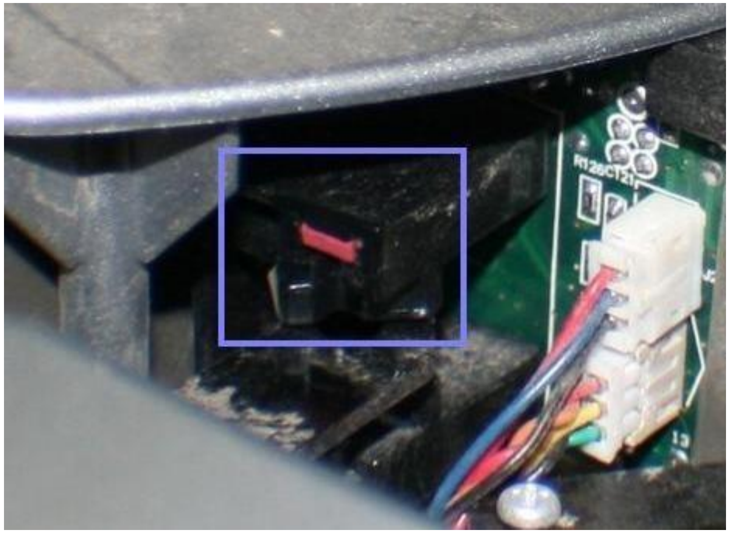
- The optical interrupter adds a physical barrier that is inserted between the emitter and detector to indicate some event.
- The Roomba's motors have a toothed disk that rotates between an emitter/detector pair.
- Each pulse of light received by the detector indicates some number of degrees of rotation.

e/d Configuration for the Bump Detection



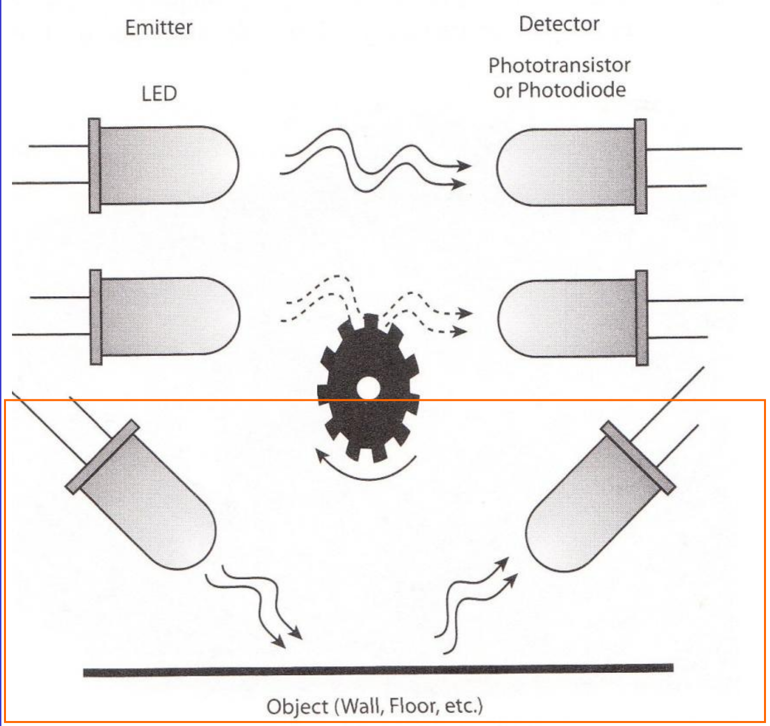






Source: http://www.robotreviews.com/chat/viewtopic.php?f=4&t=10969

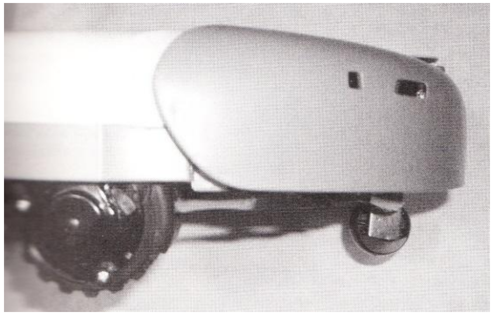
e/d Configuration for the Cliff Detection

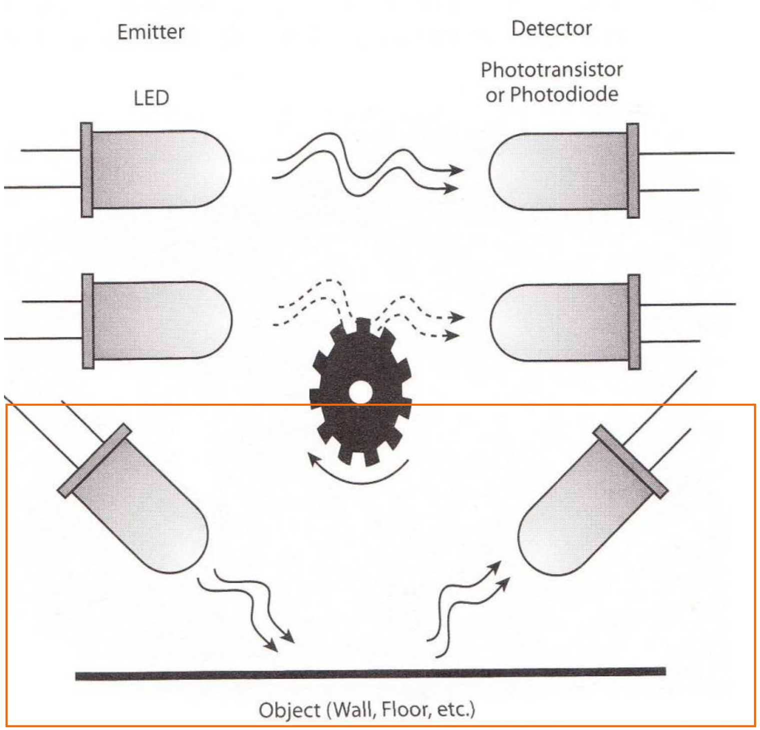


- This configuration places the emitter and detector at certain angles so they don't directly see each other and instead point toward something that may be there.
- If an object is present, the LED's light is reflected by it and the detector sees it.

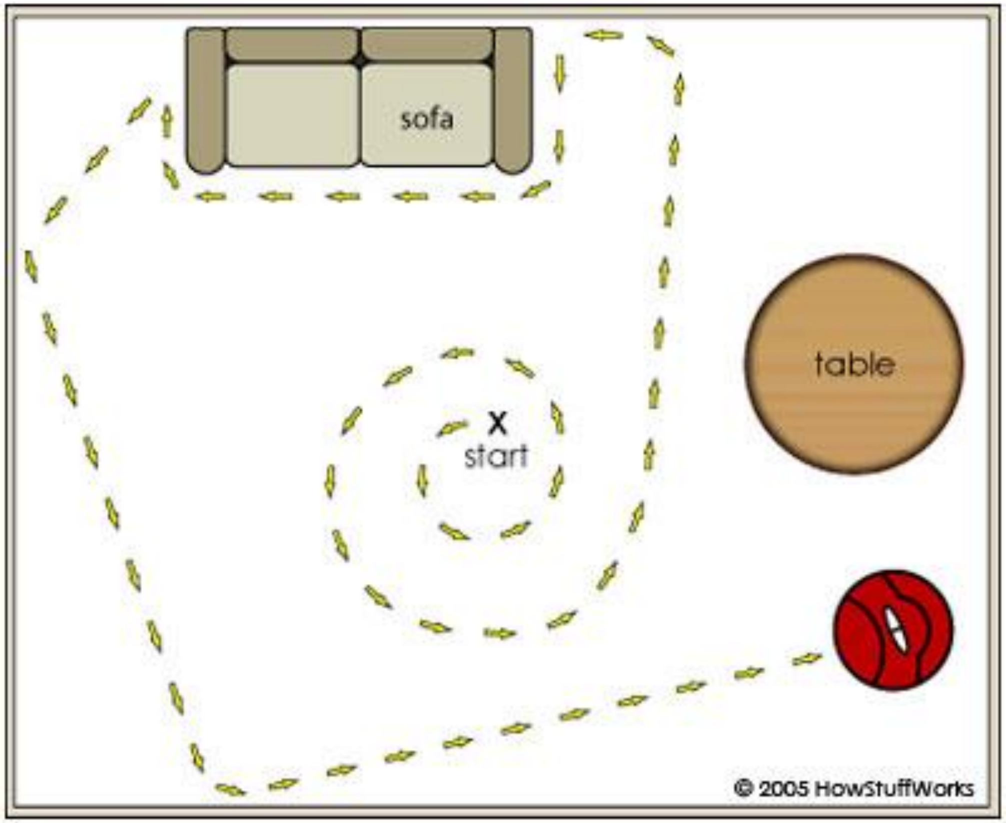
Source: Kurt, Hacking Roomba, 2007

e/d Configuration for the Wall Detection

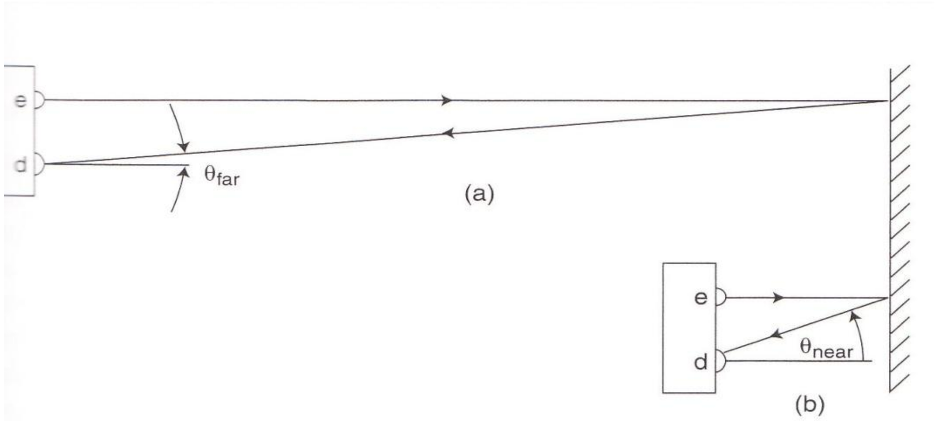




Source: Kurt, Hacking Roomba, 2007



IR Range Sensor

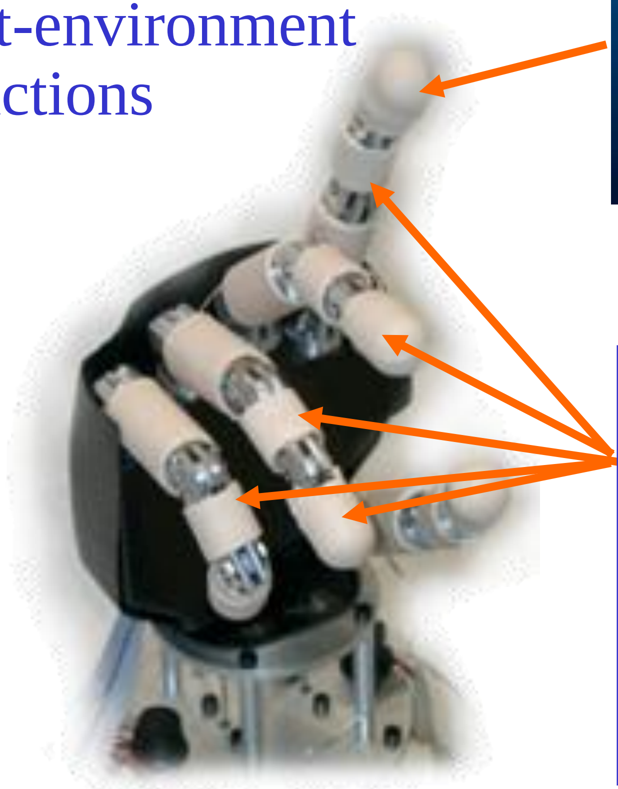


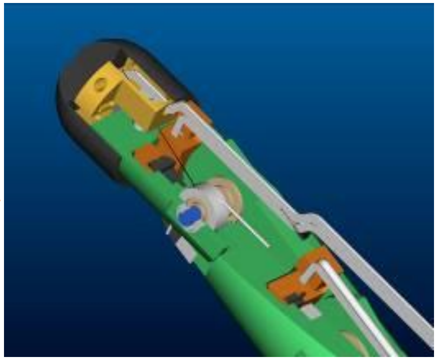
- An IR range sensor determines the distance between sensor and object using triangulation.
- The emitter, e, projects a spot of IR light on the object whose range is to be determined. A lens in the detector, d, casts an image of the emitter created spot on internal photosensitive components of the detector.
- These components are sensitive to the position (and hence the angle) of the spot's image. The angle is interpreted as a range.
- In (a), the small angle θ_{far}, implies a long distance while the large angle θ_{near} in (b), corresponds to a short distance.
- The output of the sensor may not be linear over the entire range and the values reported may be unreliable when objects are too near or too far away.

CyberHand

Exteroceptors

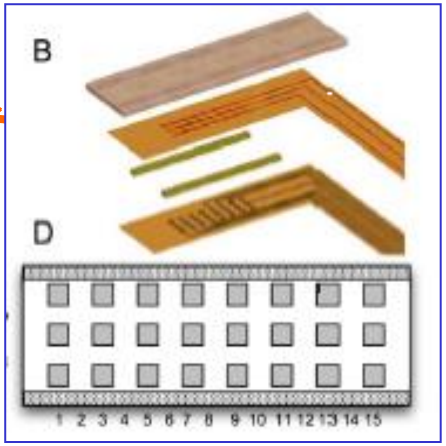
For sensing hand-object-environment interactions





Intrinsic Sensor

Three-axial strain gauge force sensors



Extrinsic Sensor

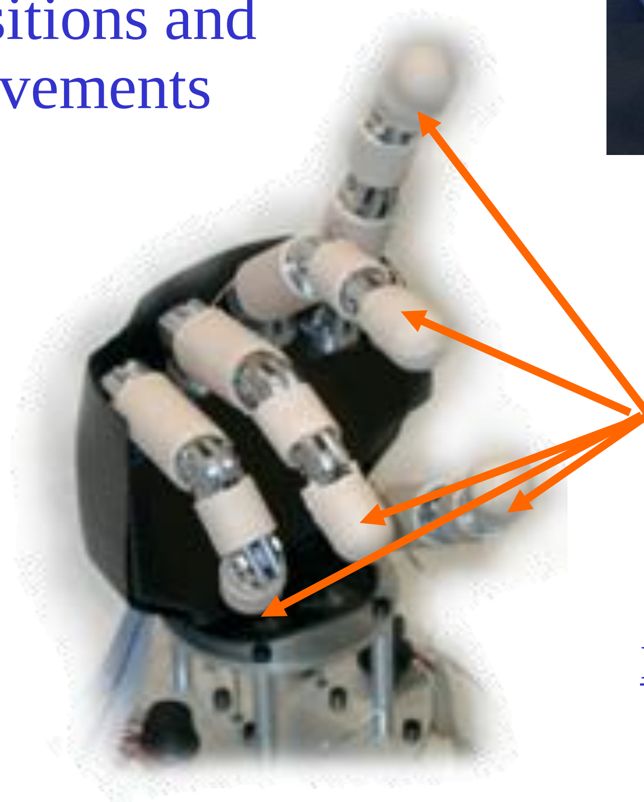
Distributed contact sensors

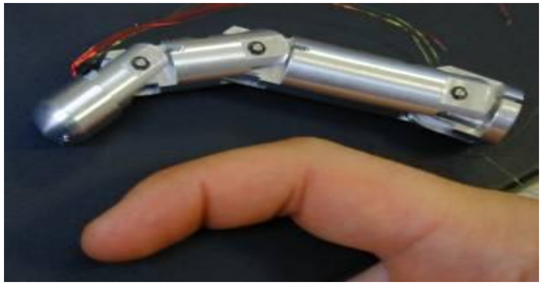
Edin BB, Ascari L, Beccai L, Roccella S, Cabibihan JJ and Carrozza MC (2008) Brain Research Bulletin

CyberHand

Proprioceptors

For sensing joint positions and movements





Embedded Joint Angle Sensors

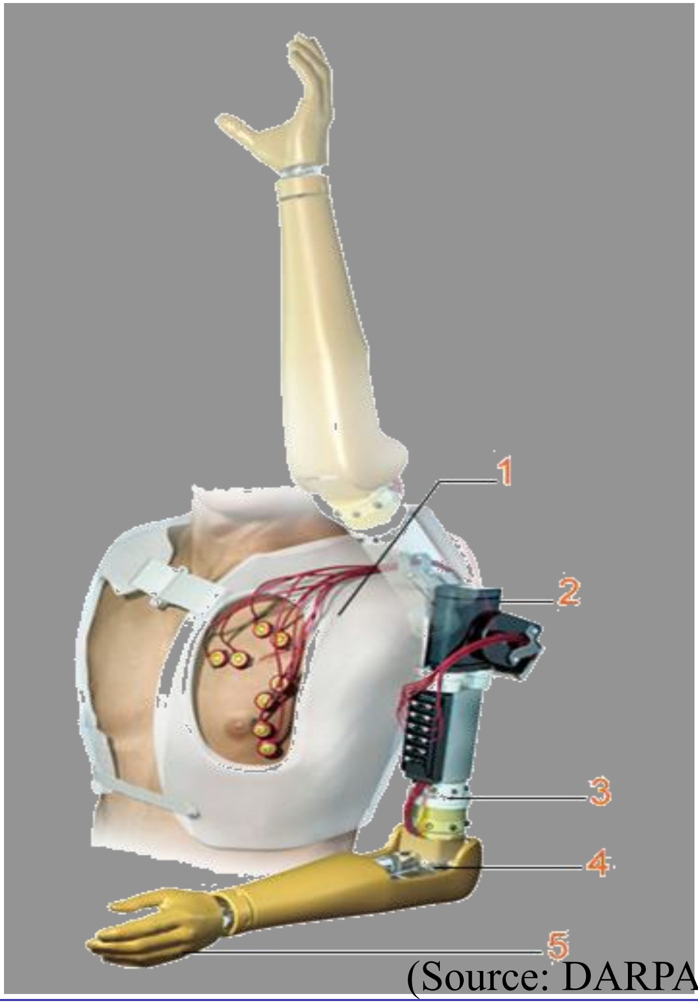
(Hall Effect)

Cable/Tendon Tension Sensors

Encoders in the Actuation System

Edin BB, Ascari L, Beccai L, Roccella S, Cabibihan JJ and Carrozza MC (2008) Brain Research Bulletin

Brain-powered artificial arm



1. THE SURGERY
Doctors rewired four nerves that once connected to Jesse Sullivan's arm and transferred them to his chest muscles. Brain signals fire the nerves and trigger electrodes affixed to his chest. A computer converts the data into action.

2. THE SHOULDER
The world's only motorized shoulder is made of aluminum and carbon fiber and weighs 1.8 pounds. A 14.8-volt lithium-ion battery drives a motor and gearbox.

3. THE HUMORAL ROTATOR
This one-motor joint enables Sullivan to move his forearm close to his midline, simplifying tasks such as buttoning a shirt.

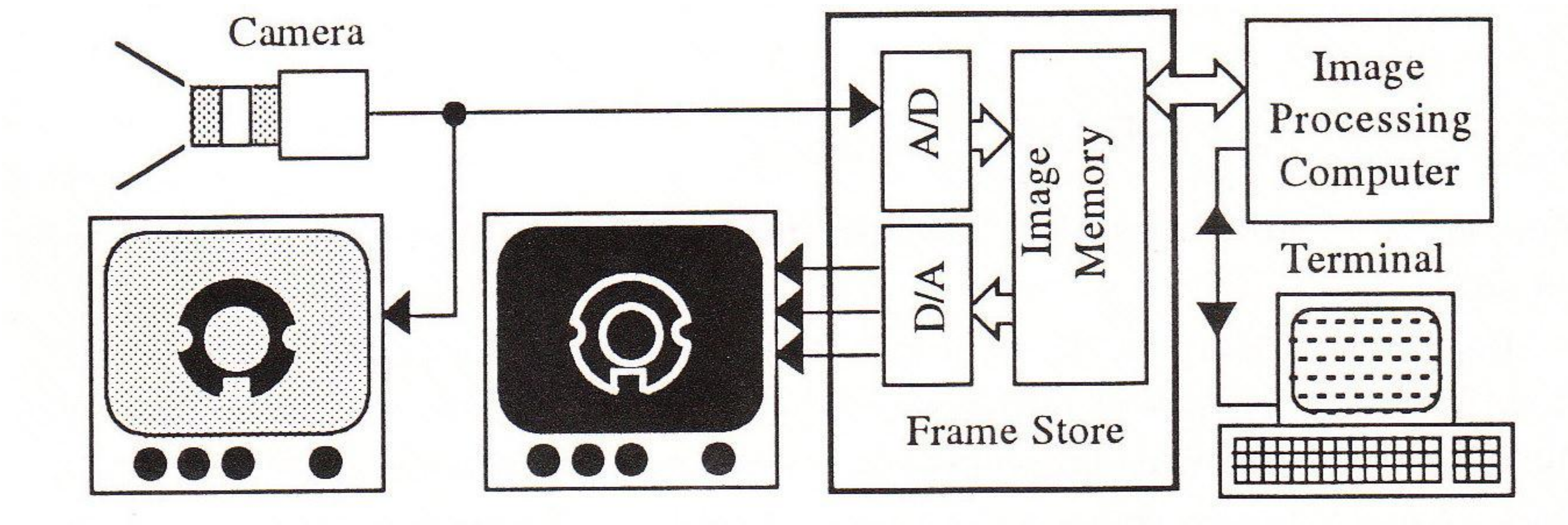
4. THE CONTROL UNIT
A 64-bit microprocessor embedded in the forearm coordinates movement of five motorized joints.

5. THE HAND
The hand features a flexible, motorized wrist. Fingertip sensors enable pressure sensation.

(Source: DARPA's Revolutionizing Prosthetics Project)

1. What is Machine Vision? (in 30 secs)
2. Case studies
3. System design for MV
4. Design issues

Machine Vision System Design



Organization of a machine vision system. The frame store is a digital memory with circuitry to digitize video signals from a camera, display images on a monitor, and transfer data between the frame store and the computer's main memory.

Batchelor and Waltz (1993)

Benefits of Machine Vision Systems

Machine Vision can be used throughout the manufacturing process to improve product quality, reduce waste, and enhance brand image:

- Eliminate defects
  - inspect 100% of products, and ensure that shipments are defect free
- Verify assembly
  - reduce waste by detecting process errors early, before thousands of items have to be scrapped.
- Automate production
  - more efficient use of manufacturing lines by giving production equipment the ability to automatically locate and identify items.
- Track and identify parts
  - automate tracking of parts and products by reading 1D and 2D identifying codes. Traceability systems using vision enable greater customization in manufacturing, and can help to verify warranties and reduce risk in the event of a product recall.

Machine Vision System Design (Specifics)

1. Mechanical handling of the objects to be examined.
2. Illumination.
3. Optics and the spatial relationship of the camera to the lighting and object under examination.
4. Camera or other image sensor.
5. Electronic signal processing at high speed.
6. Conversion of the video data into digital form.
7. Intelligent image analysis algorithms.
8. Computer hardware and architecture.
9. Computer software.
10. Environmental protection and other aspects of industrial engineering.
11. The integration of the inspection machine into existing quality assurance manufacturing practices.
12. The acceptance of the inspection machine by the personnel in the factory.
13. The cost, speed, accuracy, reliability, size, and ease of maintenance of the inspection machine.

Batchelor and Waltz (1993)

Some design/implementation issues

- Machine vision systems require a mixture of technologies to build a complete system. Clearly, the task is mechatronic system integration!
- There is a need to consider and balance all these factors.
- The optical environment must be controlled to make the image processing easier, i.e. control the lighting against gross variations, make judicious use of lenses, mirrors, a regulated power supply for the lamp and fiber-optic light guides.
- Modify the product (e.g. add markers on the PCB for alignment)

Batchelor and Waltz (1993)

Strain Sensors

Strain and Stress

- Strain is the result of the application of forces to solid objects. The forces are defined in a special way described by the general term stress.
- The effect of applied force is referred to as stress, and the resulting deformation as a strain.
- Three most common types of stress-strain relationships: tensile stress-strain, compressional stress-strain and shear stress-strain.

Strain Sensors

Tensile Stress-Strain

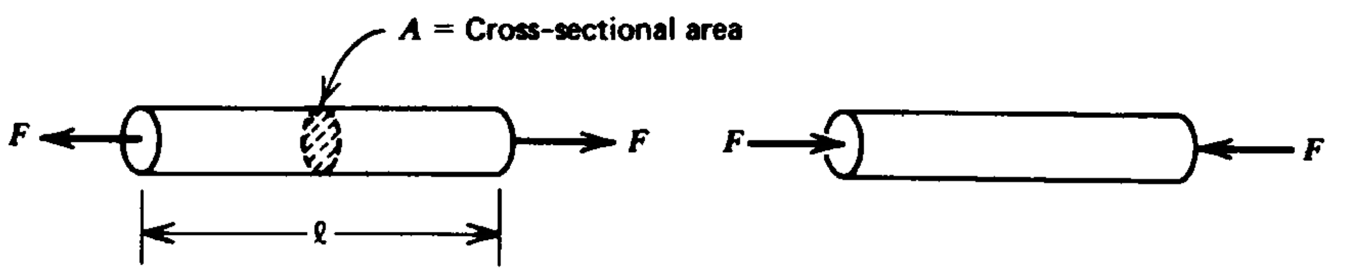
Tensile Stress = F / A

where: F = applied force in N

A = cross-sectional area of the sample in m^2

The units of stress are N/m^2 in SI units

(or $lb/in.^2$ in English units), similar to pressure



a) Tensile stress applied to a rod

b) Compressional stress applied to a rod

Tensile and compressional stress can be defined in terms of forces applied to a uniform rod.

Strain Sensors

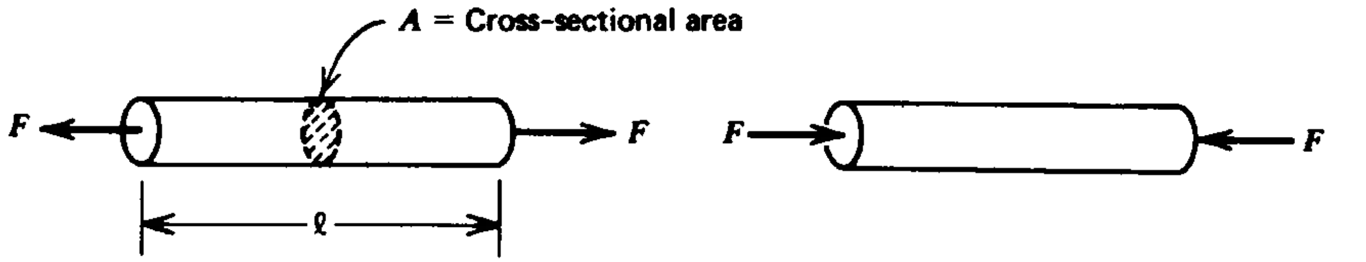
Tensile Stress-Strain

Tensile Strain = Δl / l

where: Δl = change in length in m (or in.)

l = original length in m (or in.)

Strain is a unit-less quantity



a) Tensile stress applied to a rod

b) Compressional stress applied to a rod

Tensile and compressional stress can be defined in terms of forces applied to a uniform rod.

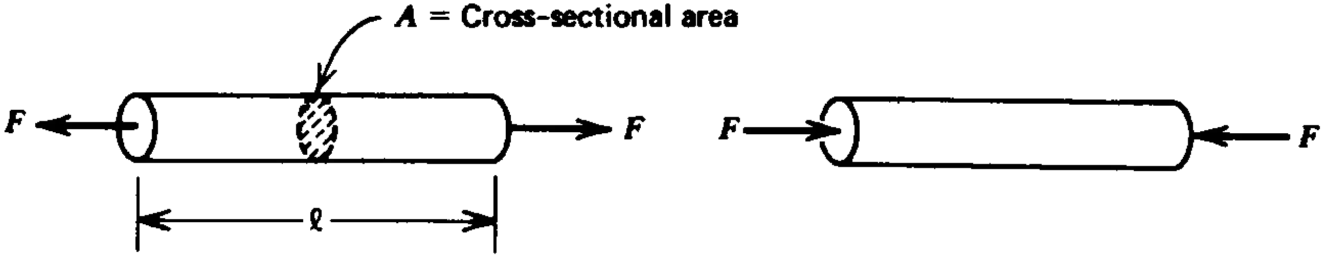
Strain Sensors

Compressional Stress-Strain

Compressional Stress = F / A

Compressional Strain = Δl / l

- The only differences are the direction of the applied force and the polarity of the change in length.
- Compressional stress, the force presses on the sample. Compressional strain, the sample decrease in length



a) Tensile stress applied to a rod

b) Compressional stress applied to a rod

Tensile and compressional stress can be defined in terms of forces applied to a uniform rod.

Strain Sensors

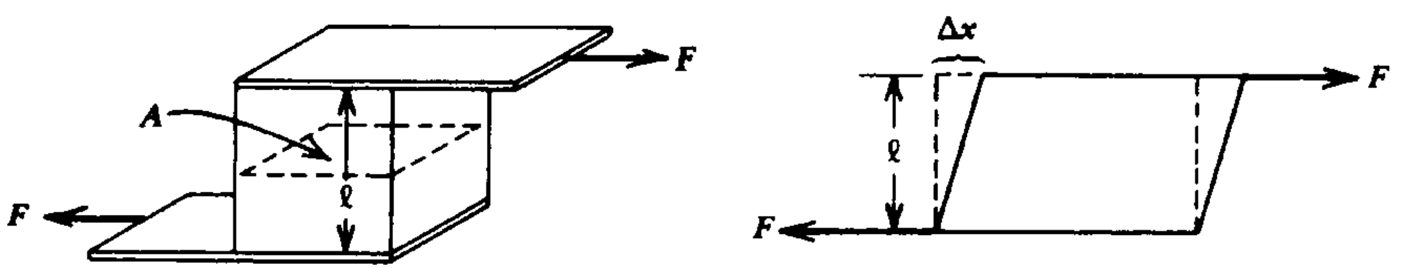
Shear Stress-Strain

Shear Stress = F / A

where: F = applied force in N

A = cross-sectional area of sheared member in m^2

The force is applied as a couple (i.e. not along the same line), tending to shear off the solid object that separates the force arms.



a) Shear stress results from a force couple

b) Shear stress tends to deform an object as shown

Shear stress is defined in terms of forces not acting in a line (a couple), which deform a member linking the forces.

Strain Sensors

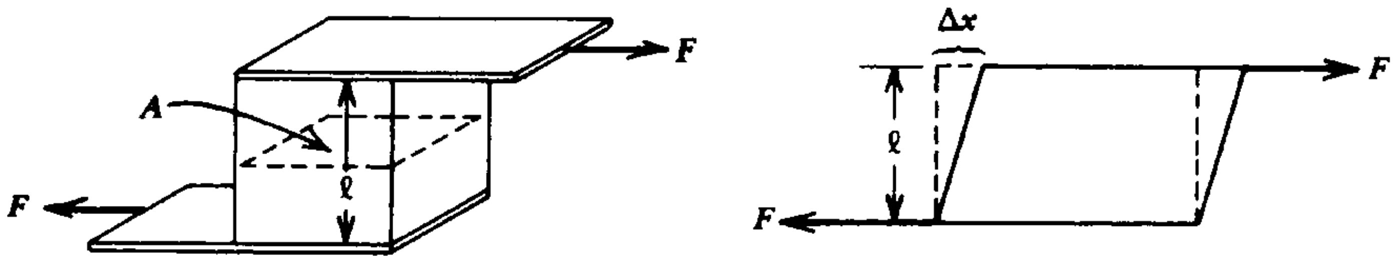
Shear Stress-Strain

Shear Strain = Δx / l

where: Δx = deformation in m

l = width of the sample in m

The strain is defined as the fractional change in dimension of the sheared member.



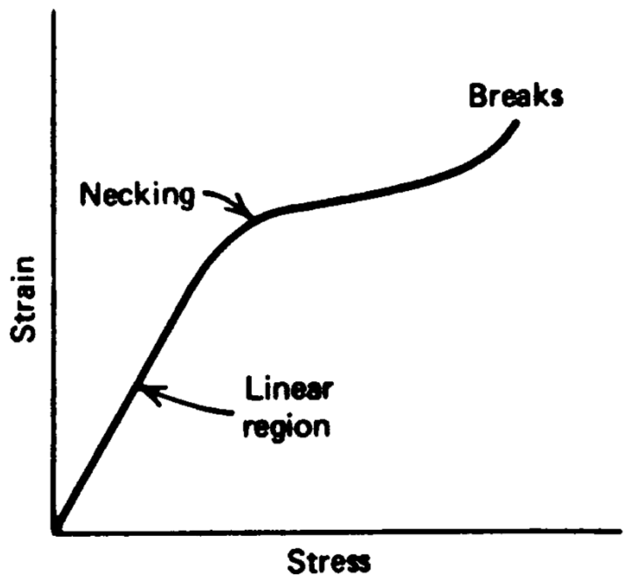
a) Shear stress results from a force couple

b) Shear stress tends to deform an object as shown

Shear stress is defined in terms of forces not acting in a line (a couple), which deform a member linking the forces.

Strain Sensors

Stress-Strain Curve

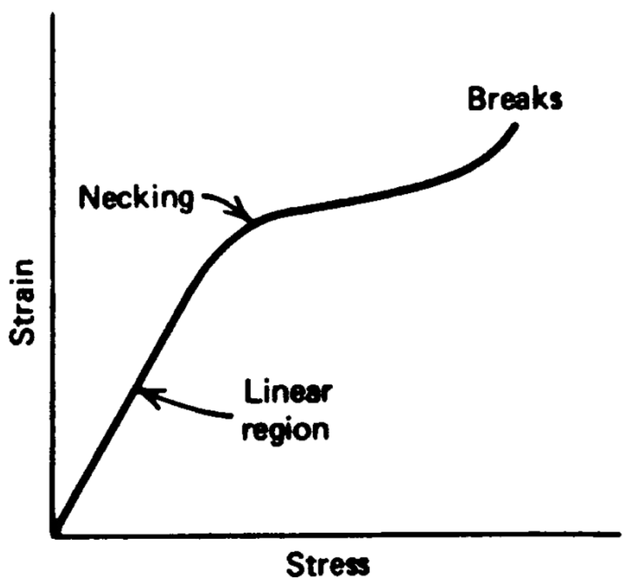


A typical stress-strain curve showing the linear region, necking, and eventual break.

- The relationship between stress and strain is linear over some range of stress.
- If the stress is kept within the linear region, the material is essentially elastic in that if the stress is removed, the deformation is also gone.
- If the elastic limit is exceeded, permanent deformation results. The material may begin to 'neck' and finally break.

Strain Sensors

Stress-Strain Curve



A typical stress-strain curve showing the linear region, necking, and eventual break.

- The linearity and slope are constant of the type of material only.
- In T and C stress, this constant is called modulus of elasticity or Young's modulus.

$$E = \text{stress} / \text{strain}$$
$$= (F / A) / (\Delta l / l)$$

where:

stress = F / A in N/m^2

strain = $\Delta l / l$ unitless

E = modulus of elasticity

Strain Sensors

Modulus of Elasticity

Material	Modulus (N/m^2)
Aluminum	68.9×10^9
Copper	117.3×10^9
Steel	207.0×10^9
Polyethylene (plastic)	34.5×10^9

Q3: Strain Sensors

Find the strain that results from a tensile force of 1000 N applied to a 10 m aluminum beam having a 4×10^{-4} m^2 cross-sectional area.

The E of aluminum is 68.9×10^{9} N/m^2

$$E = (F / A) / (\Delta l / l)$$

$$\text{Strain} = F / EA$$

$$= 10^3 \text{ N} / (4 \times 10^{-4} \text{ m}^2)(68.9 \times 10^{9} \text{ N/m}^2)$$

$$= 3.63 \times 10^{-5} \text{ or } 36.3\ \mu\text{m/m}$$

Strain Gauge Principles

Measurement Principles

- The basic technique of strain gauge (SG) measurement involves attaching (gluing) a metal wire or foil to the element whose strain is to be measured.
- As stress is applied and the element deforms, the SG material experiences the same deformation.
- Because strain is a fractional change in length, the change in SG resistance reflects the strain of both the gauge and the element to which it is secured.

Strain Sensors

Strain Gauge Principles

The resistance of a metal sample is given by:

$$R_0 = \rho \, l_0 / A_0 \qquad (1)$$

$R_0 =$ sample resistance Ω

ρ = sample resistivity $\Omega \cdot m$

l_0 = length in m

A_0 = cross-sectional area in m^2

- Suppose this sample is now stressed by the application of a force, F. Then we know that the material elongates by some amount, Δl, so that the new length is $l = l + \Delta l$.

Strain Sensors

Strain Gauge Principles

- It is also true that in such condition, although the sample lengthens, its volume will remain nearly constant. Because the volume unstressed is V = $l_0 A_0$,its follows that if the volume remains constant and the length increases, then the area must decrease by some amount, ΔA:

$$V = l_0 A_0 = (l_0 + \Delta l)(A_0 + \Delta A) \qquad (2)$$

- Because both the length and area have changed, we find the resistance of the sample will have also changed:

$$R = \rho\, (l_0 + \Delta l) / (A_0 + \Delta A) \qquad (3)$$

Strain Sensors

Strain Gauge Principles

- Using equations (2) and (3), the reader can verify that the new resistance is approximately given by:

$$R = \rho\ (l_0 / A_0)\ \ (1 + 2\ \Delta l / l_0)$$

  - Recall from equation (1) that the resistance is

$$R_0 = \rho\ l_0 / A_0$$

- From which we conclude that the change in resistance is:

$$\Delta R \sim 2R_0\ (\Delta l / l_0)$$

Strain Sensors

Strain Gauge Principles

$$\Delta R \sim 2R_0\,(\Delta l/\,l_0)$$

- This is the basic equation that underlies the use of metal strain gages because it shows that strain converts directly into a resistance change.

Strain Gauge Principles

Find the approximate change in a metal wire of 120 Ω that results from a strain of 1000 μm/m.

We can find the change in gauge resistance from:

$$\Delta R \sim 2R_0\,(\Delta l/l)$$

$$\Delta R \sim (2)(120)(10^{-3})$$

$$\Delta R = 0.24\ \Omega$$

Strain Gauge Principles

Temperature Effects

- Metals used in SG construction have linear temperature coefficients of $\alpha \sim 0.004/^\circ C$
- Temperature changes of $1^\circ C$ are not uncommon in measurement conditions in the industrial environment.

$$R(T) = R(T_0)[1 + \alpha_0 \Delta T] \quad or \quad \Delta R = R_0 \alpha_0 \Delta T$$

- ΔR = resistance change due to temp change; $\alpha_0 = 0.004/^\circ C$; $\Delta T = 1^\circ C$; $R_0 = 120\ \Omega$ nominal resistance of metal wire
- $\Delta R_T = 0.48\ \Omega$, which is twice the change because of strain. Temperature effects can mask the strain effects.

Strain Sensors

Metal Strain Gauges

Gauge Factor

An SG specification always indicates the correct relation through statement of gage factor (GF)

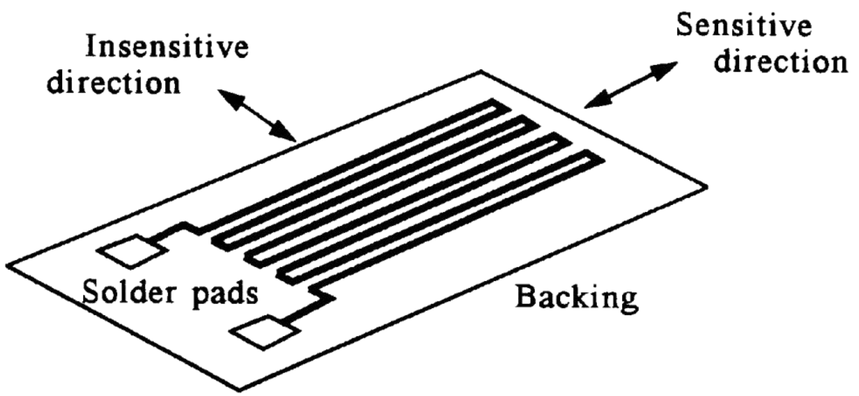
$$GF = (\Delta R / R) / (\Delta l / l)$$

where: $\Delta R / R$ = fractional change in gauge resistance due to strain; $\Delta l / l$ = strain

- For metal SG, GF is always close to 2.
- For some special alloys and carbon gauges, GF may be as large as 10.
- A high gauge factor is desirable because it indicates a larger change in resistance for a given strain and is easier to measure

Strain Sensors

Metal Strain Gauges



A metal strain gauge is composed of thin metal deposited in a pattern on a backing or carrier material.

Construction

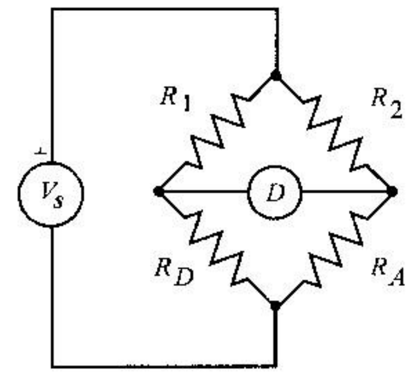
- Two forms: wire and foil.
- Gauge sensitivity is often made unidirectional, i.e. responds to strain in only one direction.
- From the figure, by folding the material back and forth, a long length can be achieved to provide high resistance.
- If strain is applied transversely to the SG length, the pattern will tend to unfold rather than stretch, with no change in resistance.
- Typical nominal SG resistance (no strain) available: 60, 120, 240, 350, 1000 Ω. The most common value is 120 Ω.

Strain Sensors

Metal Strain Gauges

Signal Conditioning

- Two effects are critical:
  - The small, fractional changes in resistance that require carefully designed resistance measurement circuits. A good SG system might require a resolution of 2 μm/mm strain.



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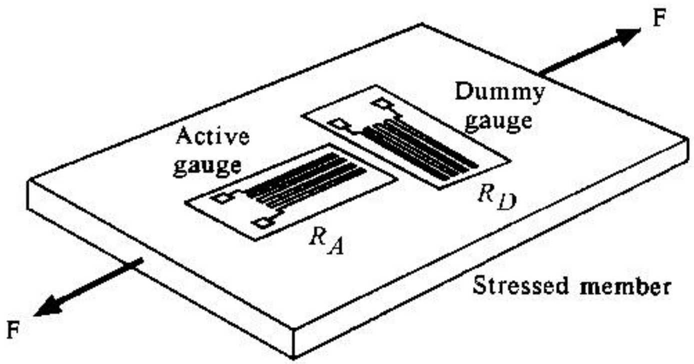


(b)

Strain gauges are used in pairs to provide temperature compensation. In some cases, such as this, only one gauge actually deforms during stress.

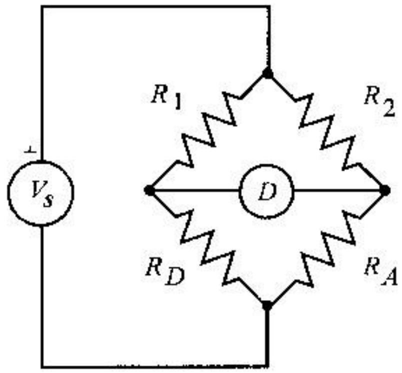
Strain Sensors

Metal Strain Gauges

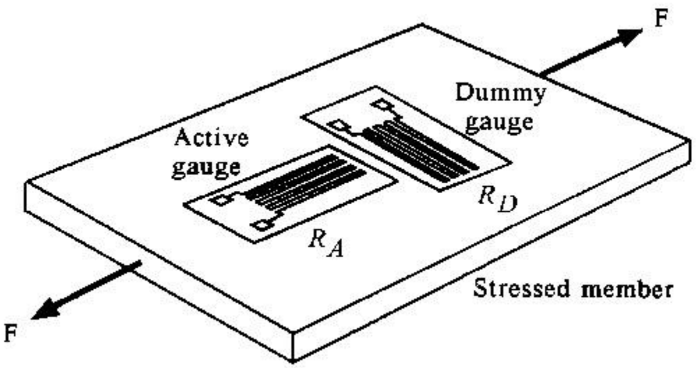
Signal Conditioning

– The second effect is the need to provide some compensation for temperature effects to eliminate masking changes in strain.

The bridge circuit provides answers to both effects.



(a)



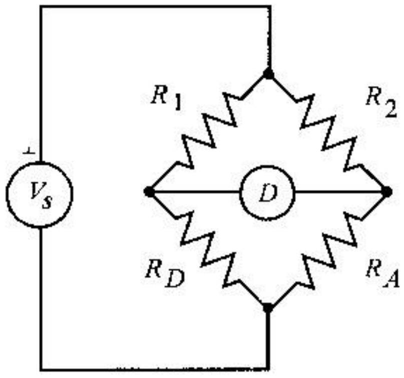
(b)

Strain Sensors

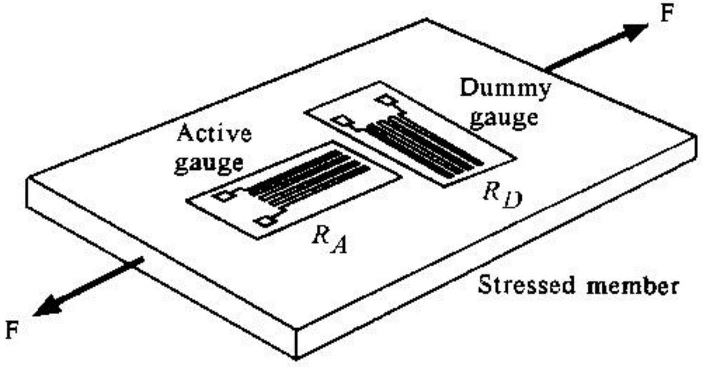
Metal Strain Gauges

Signal Conditioning

- The sensitivity of the bridge circuit for detecting small changes in resistance is well known.
- By using a dummy gauge, the required temperature compensation can be provided. The dummy gauge is mounted on the insensitive orientation but proximal to the active SG.



(a)



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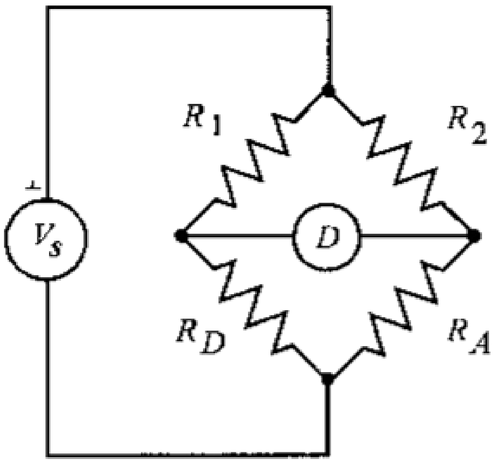
Strain Sensors

Metal Strain Gauges

Signal Conditioning



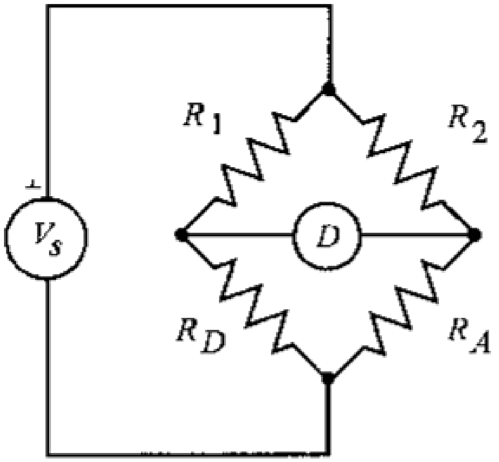
(a)

- Both gauges change in resistance from temperature effects, but the bridge does not respond to a change in both strain gauge. Only the active SG responds to strain effects, i.e. a one-arm bridge.
- The sensitivity of this bridge to strain can be found by considering the equation for bridge offset.
- Suppose $R_1 = R_2 = R_D = R$, which is the nominal (unstrained) gauge resistance. The active SG is:

$$R_A = R\,[1 + (\Delta R / R)]$$

Strain Sensors

Metal Strain Gauges



(a)

Signal Conditioning

- Suppose $R_1 = R_2 = R_D = R$, which is the nominal (unstrained) gauge resistance. The active SG is:

$$R_A = R\,[1 + (\Delta R / R)]$$

and the bridge off-null voltage is:

$$\Delta V = V_s\,[(R_D / (R_D + R_1)) - (R_A / (R_A + R_2))]$$

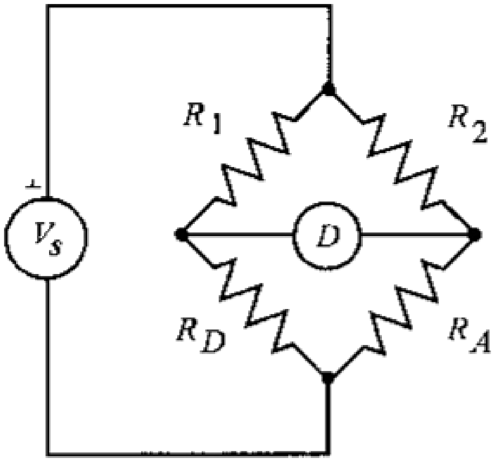
- Substituting:

$$\Delta V \sim (-Vs / 4)(\Delta R / R)$$

where the approximation is good for $(\Delta R / R) < 1$.

Strain Sensors

Metal Strain Gauges



(a)

$$\Delta V \sim (-Vs / 4)(\Delta R / R)$$

Gauge Factor

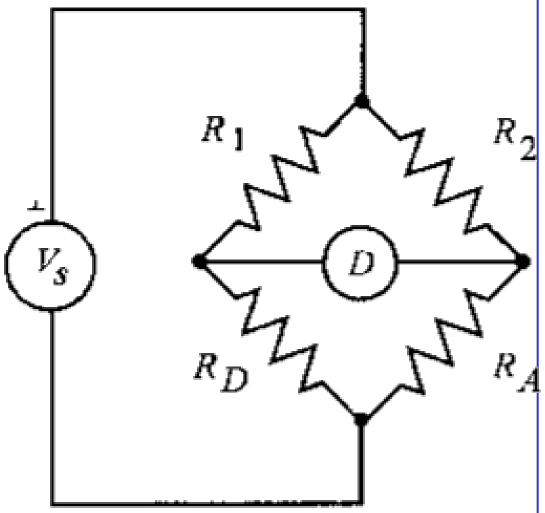
$$GF = (\Delta R / R) / (\Delta l / l)$$

After substitution:

$$\Delta V = (-Vs / 4)\ GF\ (\Delta l / l)$$

Q4: Strain Sensors

A strain gauge with GF = 2.03 and R = 350 Ω is used in a bridge in the figure. The bridge resistors are $R_1 = R_2 = 350\ \Omega$, and the dummy gauge has R = 350 Ω. If a tensile strain of 1450 μm/m is applied, find the bridge offset voltage if V_s = 10V. Find the relation between bridge off-null voltage and strain.



(a)

Q4: Strain Sensors

Solution: With no strain, the bridge is balanced. When strain is applied, the gauge resistance will change by a value given by

$$GF = (\Delta R / R) / (\Delta l / l)$$

Re-arranging: $\Delta R = (GF)(strain)(R)$

$$\Delta R = (2.03)(1.45 \times 10^{-3})(350\Omega) = 1.03\ \Omega$$

Since it's tensile strain, the resistance will increase to R = 351Ω.

The bridge offset voltage is

$$\Delta V = (RV / (R_1 + R)) - (R_A V / (R_A + R_2))$$

$$\Delta V = 5 - [(351)(10) / 701]$$

$$\Delta V = -0.007 \text{ V offset}$$

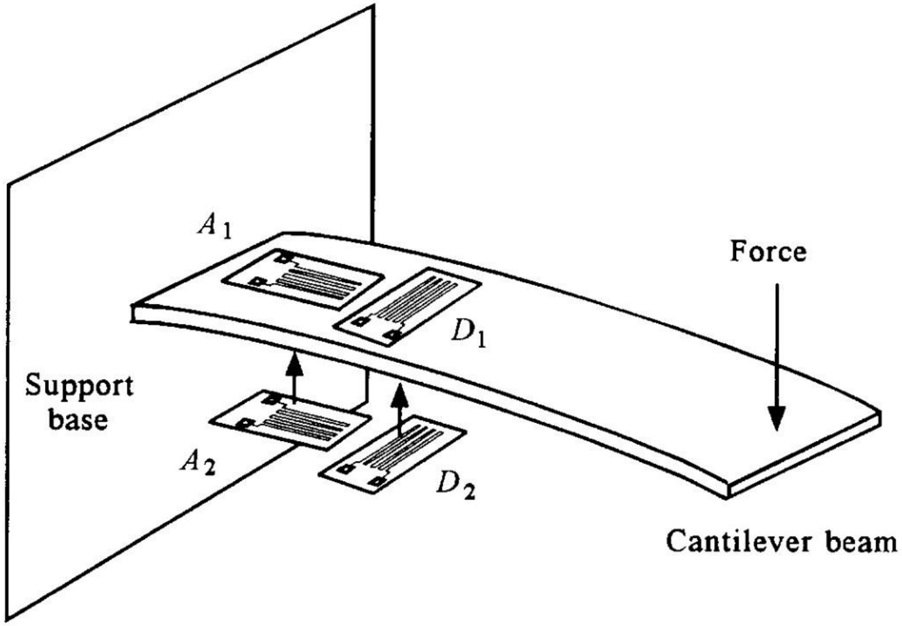
Strain Sensors

Metal Strain Gauges

- Another configuration uses active strain gauges in two arm of the bridge, and is called a two-arm bridge.
- All four arms are strain gauges, but two are for temperature compensation only.
- This has added advantage of doubling the sensitivity.
- The bridge off-null voltage in terms of strain is:

$$\Delta V = (-V_s / 2)\ GF\ (\Delta l / l)$$

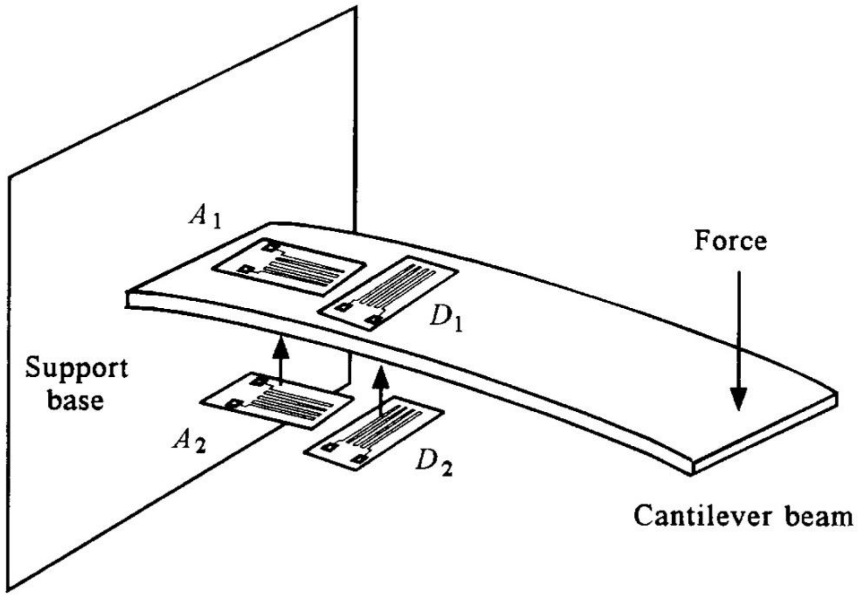
Strain Sensors



This structure shows how four gauges can be used to measure beam bending. Two respond to bending, and two are for temperature compensation.

- The beam (cantilever) is supported at only one end, and deflects as shown when a load is applied.
- For this application, it is common to use a two-arm bridge.

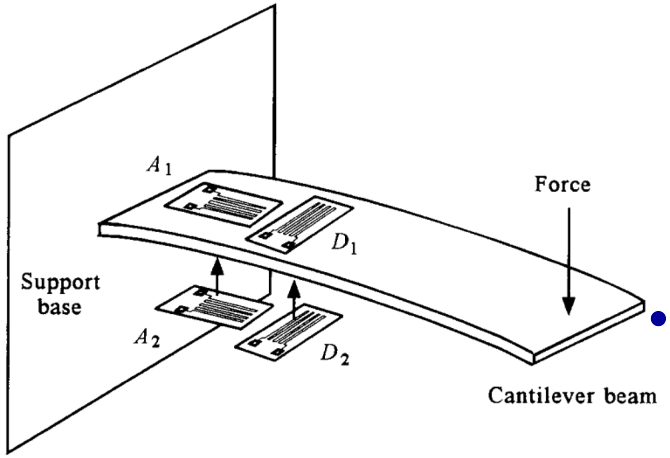
Strain Sensors

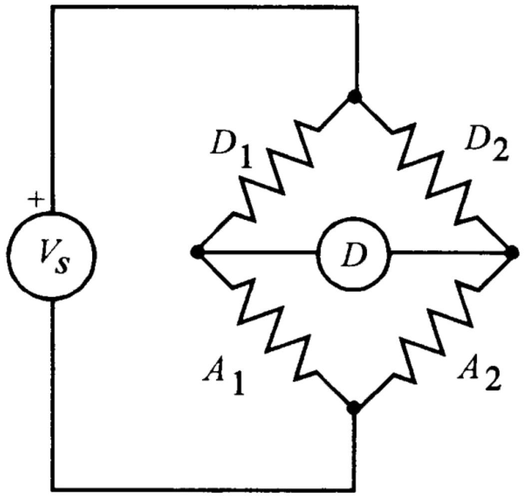


This structure shows how four gauges can be used to measure beam bending. Two respond to bending, and two are for temperature compensation.

- One pair of active (A_1) and dummy (D_1) gauges is mounted on the top surface. The active gauge will experience tension with downward deflection of the beam, and its resistance will increase.
- The second pair, A_2 and D_2, are mounted on the bottom surface.
- The active gauge will experience compression with downward deflection, and its resistance will decrease.

Strain Sensors





Connection of the 4 SG into a bridge circuit.

- The gauges must be connected so that the off-null voltages increases with strain.
- One divider voltage should increase and the other should decrease so that the difference grows. This is accomplished by using the active gauges in bridge resistor positions R_3 and R_4 of the standard bridge configuration.

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