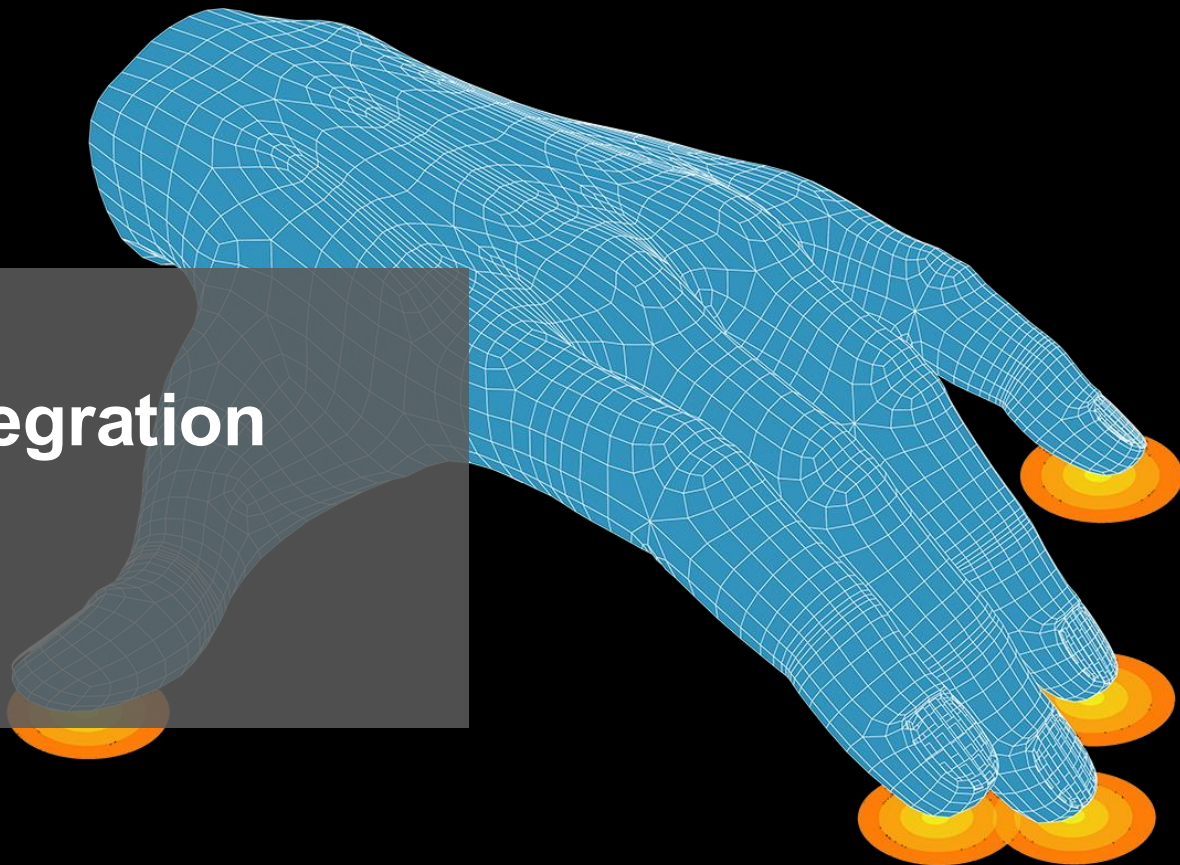




Sensors Integration

Yucheng Xia

12.10.2026



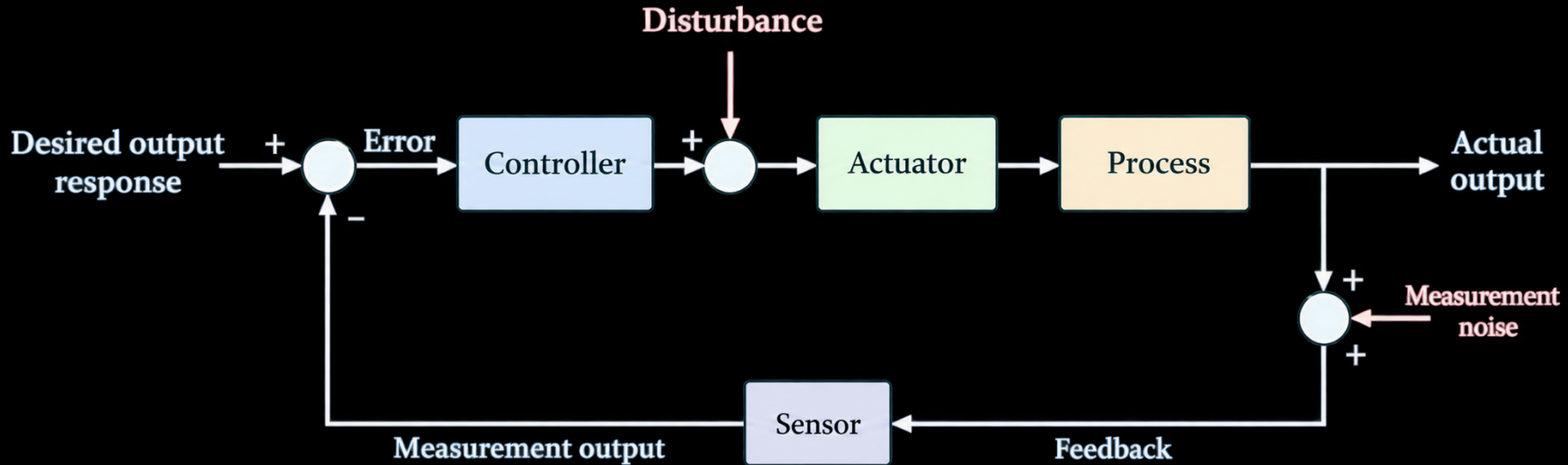


Part 1

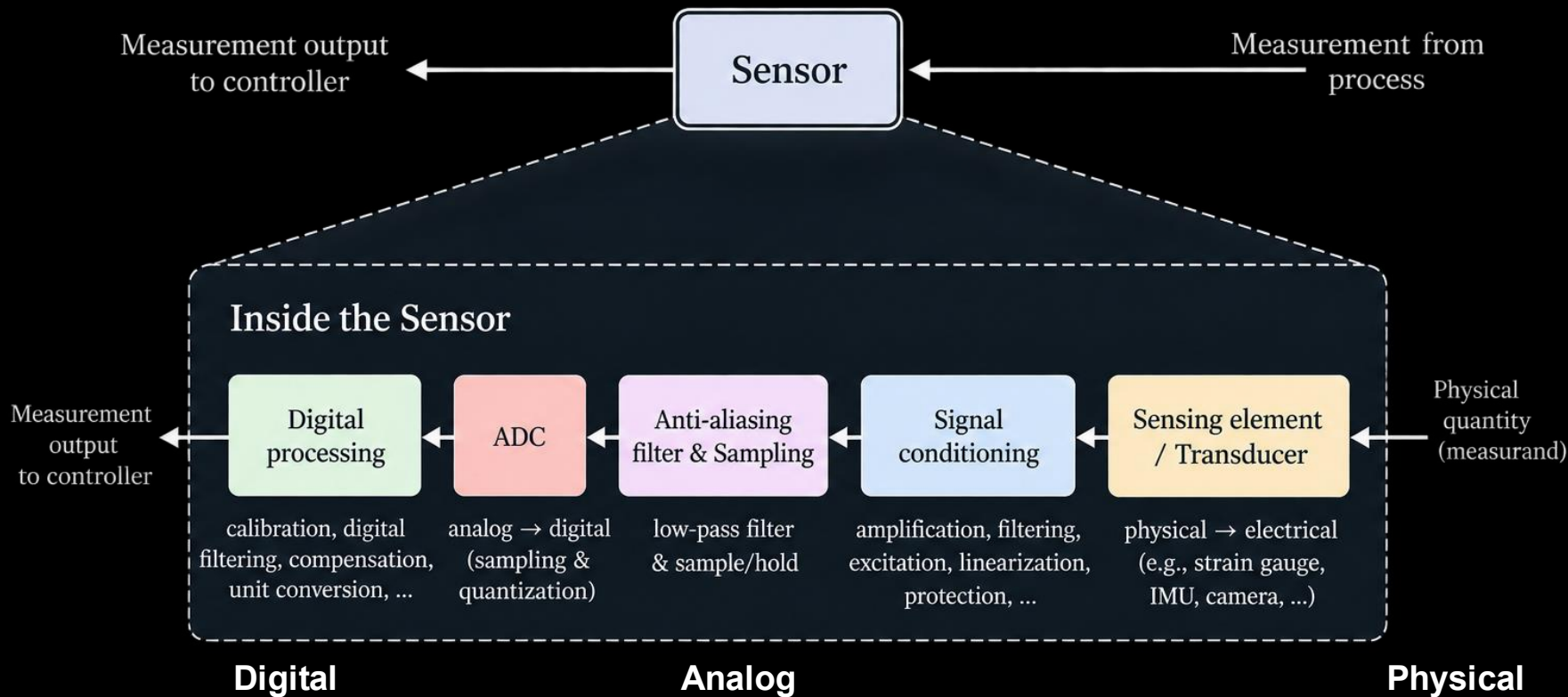
Where does sensing fit?

How does a physical quantity become information for a robot controller?

Sensors in the Robot Information Loop



Physical, Analog and Digital Domains



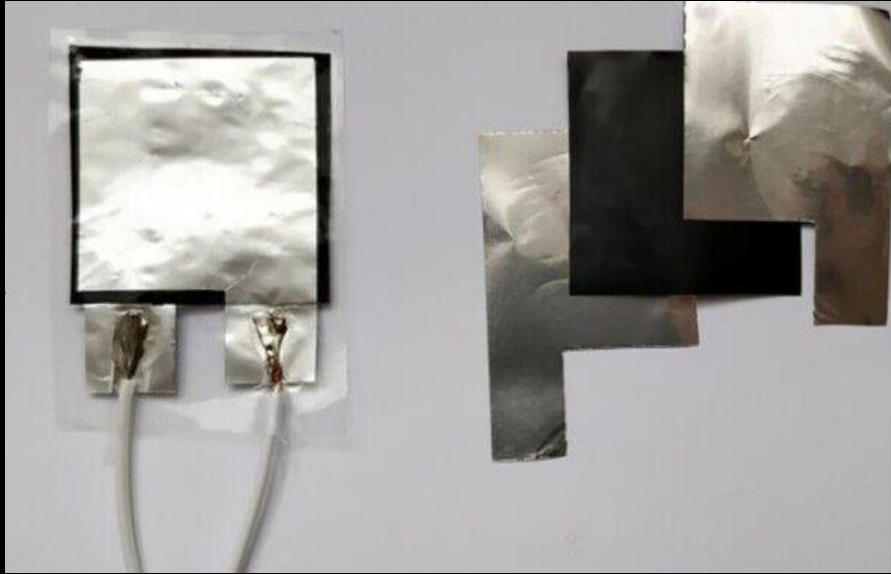


Part 2

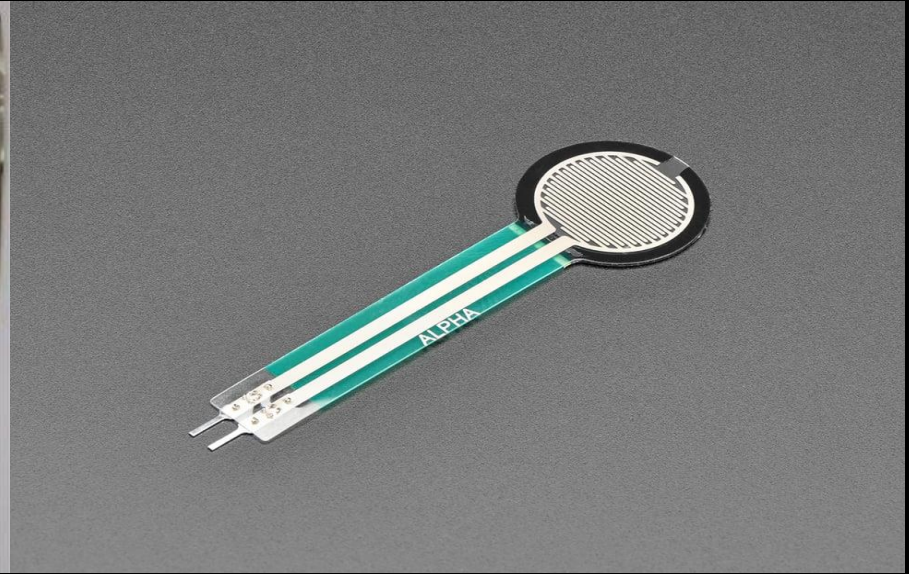
What are we actually buying?

What integration work remains at each product level?

DIY and Off-the-Shelf Sensors



Custom sensor



Commercial sensor

Sensing Element, IC, Module and Product



What you choose	What you still need to solve
Sensing material / element	Excitation, signal conversion, packaging and calibration
Sensor IC	PCB, power, electrical interface and software
Breakout module	Controller connection, data acquisition and system integration
Complete product	Communication, mounting and application configuration

BMP390: Sensor IC and Breakout Module



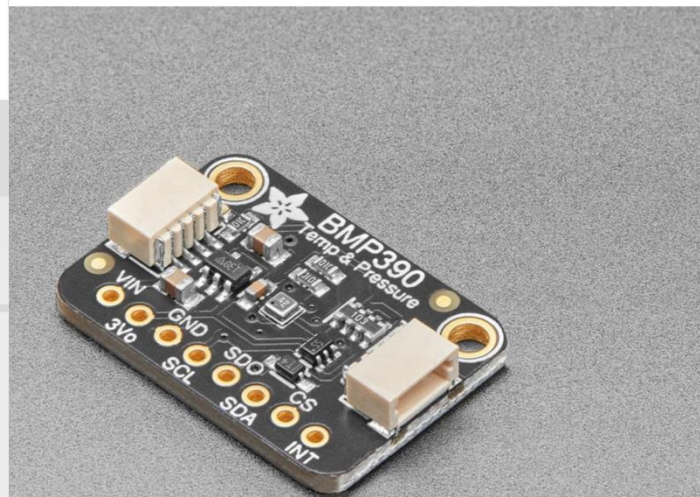
BMP390

Digital pressure sensor



Products Gift Ideas What's New

Pressure / Adafruit BMP390 - Precision Barometric Pressure and Altimeter



Adafruit BMP390 -
Precision Barometric
Pressure and Altimeter
- STEMMA QT / Qwiic

Product ID: 4816

\$10.95

In stock

1

Add to Cart

☐ Also include 1 x STEMMA QT / Qwiic JST
SH 4-pin to Premium Male Headers Cable
(\$0.95)

☐ Also include 1 x STEMMA QT / Qwiic JST
SH 4-pin Cable - 100mm Long (\$0.95)

Qty Discount

1-9 \$10.95

10-99 \$9.86

100+ \$8.76

Add to Wishlist

What Does a Sensor Module Contain?



6.3. Connection diagram I²C

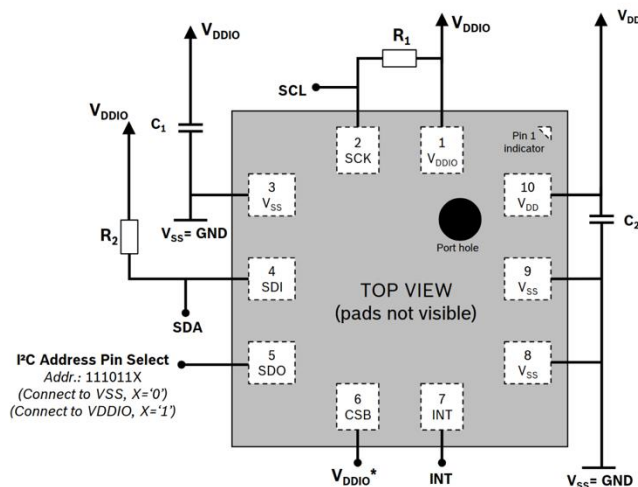


Figure 25: I²C connection diagram (Pin1 marking indicated)

Sensor IC and PCB

Power routing and decoupling

Pull-ups, connectors or level conversion when the board provides them

Firmware / library support when the supplier provides it

BMP390 application circuit shown. Board features vary by module.



How to Read a Sensor Datasheet

Supply voltage and I/O levels

Output type and interface

Range and external components

Bandwidth / sample rate

Accuracy, repeatability and calibration

Table 2: General electrical parameter specifications						
OPERATING CONDITIONS BMP390						
Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operating temperature range	T _A	operational	-40	25	+85	°C
		full accuracy	0		+65	
Operating pressure range	P	full accuracy	300		1250	hPa
Sensor supply voltage	V _{DD}	ripple max. 50mVpp	1.65	1.8	3.6	V
Interface supply voltage	V _{DDIO}		1.2	1.8	3.6	V

Read the test conditions
and min / typ / max values.

Source: Bosch Sensortec, BMP390 datasheet, Table 2



Part 3

Can the signal be trusted?

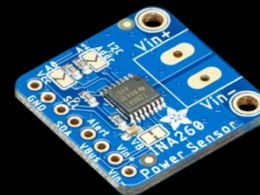
Why does a digital reading not automatically equal the quantity we need?

Analog and Digital Sensor Outputs



Analog readout

Physical response becomes a voltage.
The MCU samples it with an ADC.



Digital module

Conversion happens inside the device.
The MCU reads registers over a bus.

A digital interface still needs compatible voltage levels and timing



FSR Integration Case



Force changes resistance

A readout circuit produces voltage

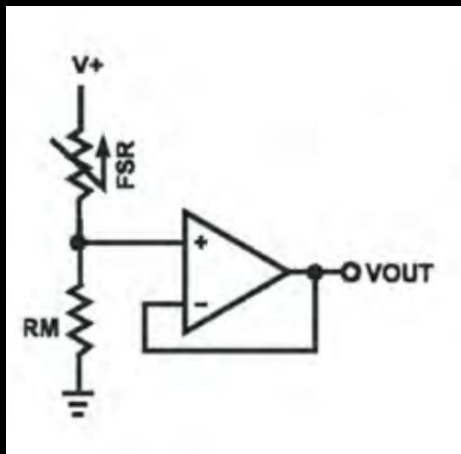
An ADC produces a code

Calibration or task logic produces
a useful output

From the Focus Talk:
An FSR changes resistance under
load.

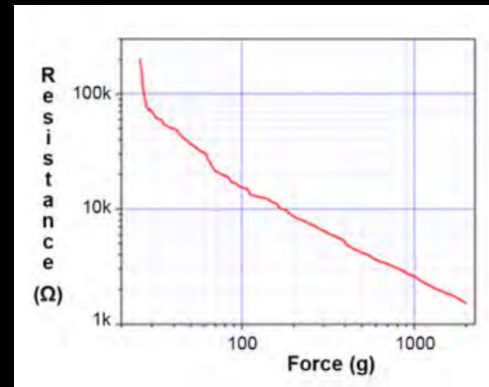


Resistance Change to Voltage



$$V_{OUT} = \frac{R_M V_+}{(R_M + R_{FSR})}$$

The resistor choice sets the useful voltage range.



Voltage-divider readout

Nonlinear response

ADC code represents voltage. Force estimation needs a mapping and calibration.

Source: RWR2025 Workshop, FSR readout circuit and characteristic curve

ADC Range and Resolution

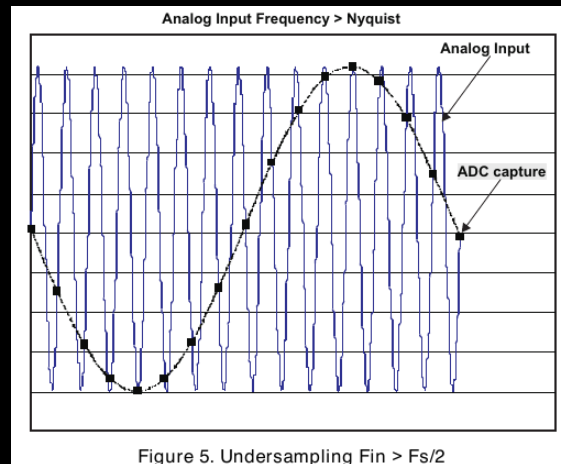
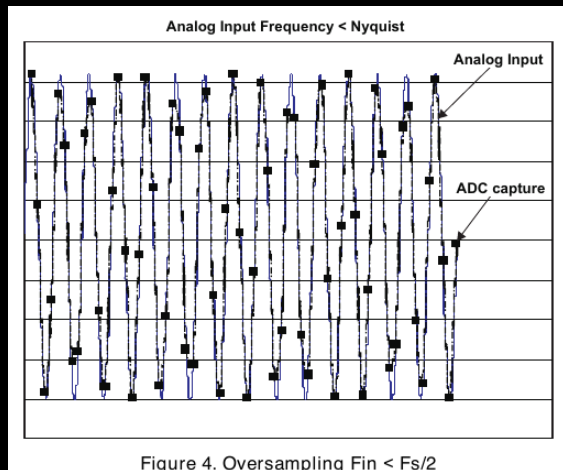


Input range	Resolution	Usable information
Signal stays within the allowed ADC range	12 bits = 4096 codes	Noise and distortion reduce effective resolution
Reference voltage sets the conversion scale	Ideal 0–3.3 V example: $3.3 \text{ V} / 4096$ $\approx 0.81 \text{ mV per code}$	More bits alone do not guarantee accurate force

Check electrical limits before interpreting the digital value.

ADC concepts: Texas Instruments, SLAA510. Numerical example assumes an ideal ADC.

Sampling, Noise and Filtering



Adequate sampling

Aliasing

Sampling rate follows
the signal bandwidth

Analog anti-alias filtering
acts before the ADC

Digital filtering reduces
noise
and can add latency

Source: Texas Instruments, SLAA510, Figs. 4–5



Filtering Before and After the ADC

Before sampling

Analog anti-alias filter
Limits input bandwidth
Works with the sampling rate

After sampling

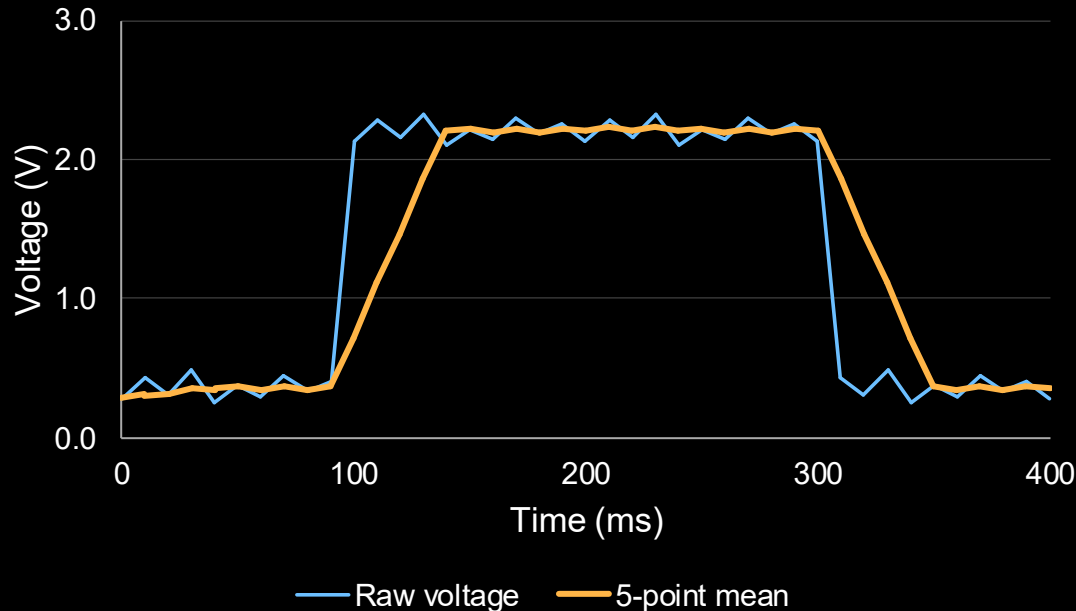
Digital filter
Smooths or rejects selected noise
Can change timing and events

Digital filtering cannot recover information lost to clipping or aliasing.
Check wiring, power and acquisition before choosing a filter.

References: TI SLAA510, S. W. Smith, The Scientist and Engineer's Guide to DSP, Chapter 15



Example 1: Moving Average for an FSR



100 samples/s
Latest 5 samples

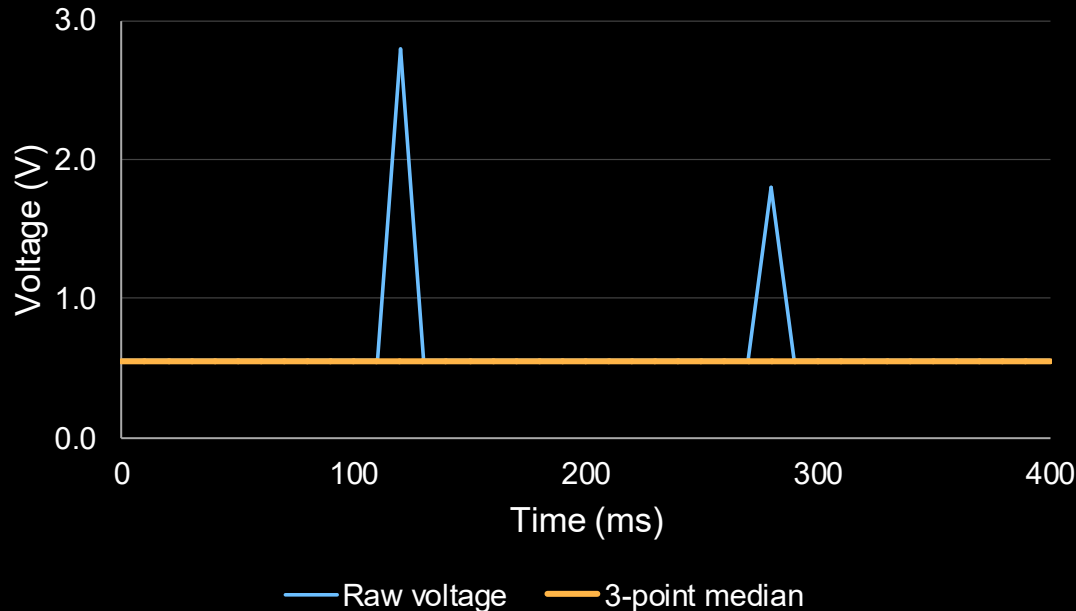
Less jitter
Slower contact
response

Group delay: 20 ms
Threshold delay also
depends
on waveform and threshold.

Synthetic teaching data. Causal average: $y[n] = (x[n] + \dots + x[n-4]) / 5$. Reference: Smith, Chapter 15



Example 2: Spikes in a Tactile Channel



120 ms: injected outlier
280 ms: brief real event

Both last one sample.
The median removes
both.

Verify which events matter.
Keep timestamps and
per-channel filter settings.

Synthetic teaching data. Causal median of latest 3 samples. Reference: MathWorks, Median Filtering

When Signal Conditioning Is Needed



Readout choice	When it helps
Voltage divider	Simple resistive changes and a suitable voltage range
Wheatstone bridge	Small differential resistance changes
Amplifier / buffer	Small signals, range adjustment or loading problems
Integrated converter	The IC already provides the required conversion

Excitation and anti-alias filtering depend on the sensor and acquisition path.

What Level of Measurement Does the Task Require?



Task need	Useful output
Contact detection	Contact / no contact
Threshold detection	Above / below a chosen threshold
Relative comparison	More / less under comparable conditions
Trend measurement	A meaningful change over time
Calibrated physical measurement	A physical value with units and known uncertainty

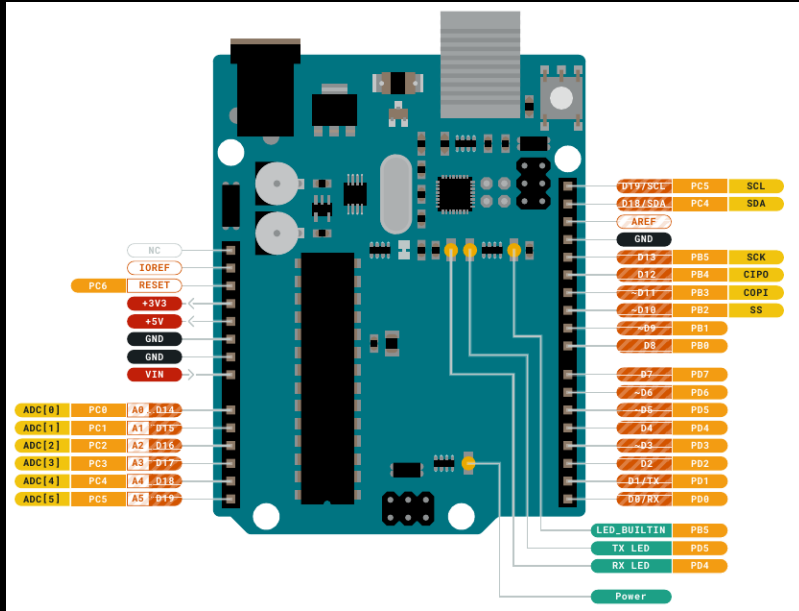


Part 4

How does it become a robotic system?

How do we build a reliable, manageable sensing subsystem?

Why Use a Microcontroller?



Sensor interfacing

Deterministic sampling and
timestamping

Basic filtering and calibration

Protocol conversion

Reduced acquisition load on the
computer

Figure: Arduino UNO Rev3 pinout, CC BY-SA 4.0

MCU, Computer and ROS



Layer	Main responsibility
Microcontroller	Acquire samples, control timing and perform local processing
Computer	Run robot-level estimation, planning and control
ROS software	Transport and organize messages, timestamps and coordinate frames

The MCU sends measurements to the host.

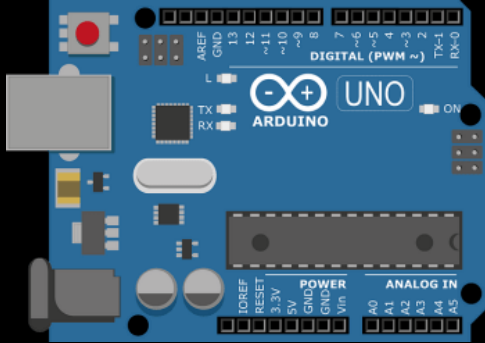
The host needs values, units, timing and sensor identity.

Analog, I²C, SPI and UART



Output / interface	Typical use	Main risks
Analog + ADC	Simple analog sensors	Noise, input range, reference voltage
I ² C	Several local digital sensors	Address conflicts, pull-ups, bus length
SPI	Higher-rate local digital sensors	More pins and routing complexity
UART	MCU to host or controller	Point-to-point link, baud rate, voltage levels

MCU and Board Selection



Arduino



Teensy



STM32

ADC channels and rate	I/O voltage	Interfaces and pin count
Timing requirements	Firmware support	Project complexity



Scaling from One Sensor to Many

One sensor

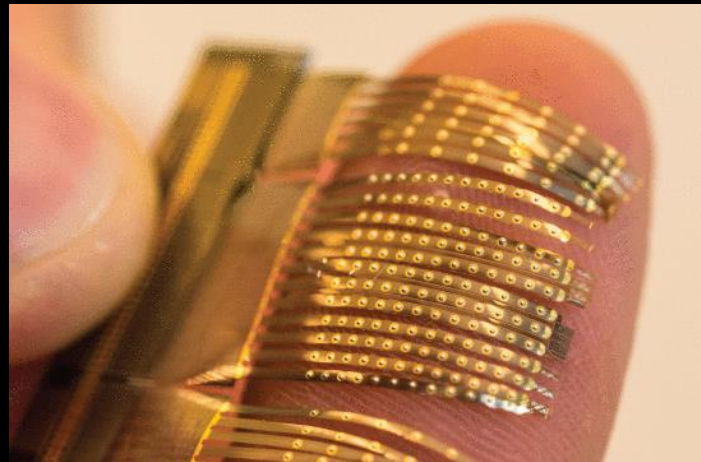
One readout path and one data stream

Many sensors

Limited ADC channels and shared buses

Lower effective rate per channel

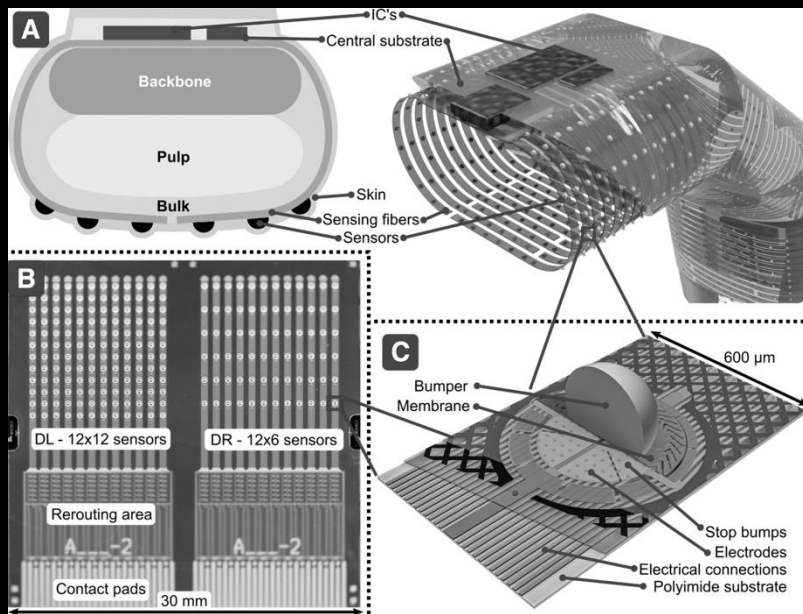
More wiring, calibration and synchronization



Array image: Weichart et al., 2021



Channel Count, Bandwidth, Wiring and Crosstalk



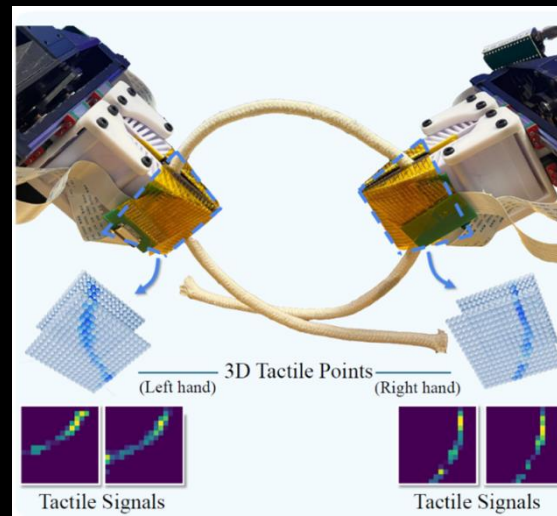
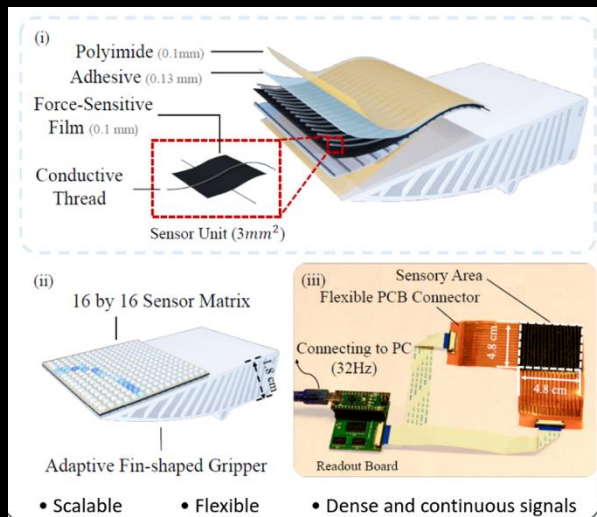
Illustrative data budget

$32 \text{ channels} \times 100 \text{ samples/s} \times 2 \text{ bytes}$
 $= 6.4 \text{ kB/s raw payload}$

Framing and timestamps add data.
Shared acquisition limits per-channel rate.
Wiring and coupling can disturb channels.
Timing determines whether samples align.

Array figure: Weichart et al., 2024. Data budget is an illustrative example.

Tactile Array Integration Case Study



Where do channels become digital data?
How do readout and communication scale?
How do tactile samples align with robot interaction?

Huang et al., 3D-VITac, PMLR 270, 2025.



Rotary Sensor Live Demo