Intent detection and somatosensory feedback

#06: Tomography (EIT, ultrasound)

Claudio CASTELLINI, Sabine THÜRAUF

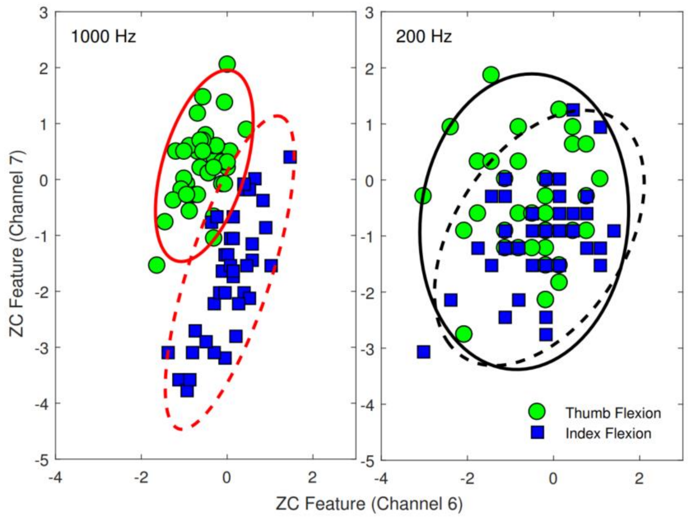

Figure 2. Differences in EMG patterns between using: (**left**) a 1000 Hz sampling rate; and (**right**) a 200 Hz sampling rate. ZC features are extracted from two different EMG channels (6 and 7) during thumb flexion (green circle markers and solid lines) and index flexion (blue square markers and dashed lines). Samples are from Subject 1 of Database 3.

EMG patterns related to two actions. Reproduced from Angkoon Phinyomark, Rami N. Khushaba and Erik Scheme, *Feature Extraction and Selection for Myoelectric Control Based on Wearable EMG Sensors*, MDPI Sensors 2018, 18, 1615

The *rubber hand illusion.* See Botvinick M, Cohen J., *Rubber hands 'feel' touch that eyes see.* Nature. 1998 Feb 19;391(6669):756. doi: 10.1038/35784. PMID: 9486643.

Lecture #06:

Tomography (EIT, ultrasound)

- Electrical Impedance Tomography (EIT)
- Ultrasound scanning (A-mode, B-mode a.k.a. imaging)
- Summary

Tomography

- all methods seen so far (sEMG, FMG/TMG, tracking) yield „surface“ information
  - what about trying to gather „deep“ information?
- we need tomography!

Tomography

From Wikipedia, the free encyclopedia

Tomography is imaging by sections or sectioning through the use of any kind of penetrating wave. The method is used in radiology, archaeology, biology, atmospheric science, geophysics, oceanography, plasma physics, materials science, astrophysics, quantum information, and other areas of science. The word *tomography* is derived from Ancient Greek τόμος *tomos*, "slice, section" and γράφω *graphō*, "to write" or, in this context as well, "to describe." A device used in tomography is called a **tomograph**, while the image produced is a **tomogram**.

In many cases, the production of these images is based on the mathematical procedure tomographic reconstruction, such as X-ray computed tomography technically being produced from multiple projectional radiographs. Many different reconstruction algorithms exist. Most algorithms fall into one of two categories: filtered back projection (FBP) and iterative reconstruction (IR). These procedures give inexact results: they represent a compromise between accuracy and computation time required. FBP demands fewer computational resources, while IR generally produces fewer artifacts (errors in the reconstruction) at a higher computing cost.[1]

Although MRI and ultrasound are transmission methods, they typically do not require movement of the transmitter to acquire data from different directions. In MRI, both projections and higher spatial harmonics are sampled by applying spatially-varying magnetic fields; no moving parts are necessary to generate an image. On the other hand, since ultrasound uses time-of-flight to spatially encode the received signal, it is not strictly a tomographic method and does not require multiple acquisitions at all.

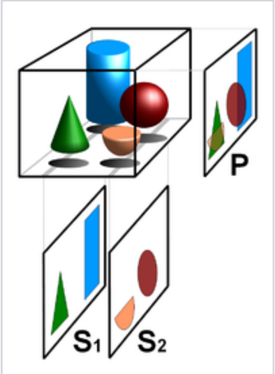

Fig.1: Basic principle of tomography: superposition free tomographic cross sections S_1 and S_2 compared with the (not tomographic) projected image P

Contents [hide]

Intent detection and somatosensory feedback

1. **Tomography** is a technique used to visualize the internal structures of an object by creating a detailed image from multiple projections. It is essentially a method to see a slice of something without physically slicing it.
2. Tomography is used to gather "deep" information about internal structures, as opposed to surface-level data provided by other methods like sEMG (surface electromyography).
3. An **interference profile** in the context of tomography refers to the pattern of waves that result from the interaction (interference) of energy waves (such as sound waves or electromagnetic waves) as they pass through and are affected by the internal structures of the tissue. This profile is crucial in reconstructing detailed images of the internal structures.
4. **Tomography Types**
5. **Type 1: Wave of Energy at Specific Angles**
   1. **Process**:
      1. A wave of energy (e.g., X-rays, sound waves) is sent into the tissue from many specific angles, rotating around the tissue.
      2. The interference profiles (patterns of how the waves interact with the internal structures) are recorded at the opposite side.
      3. These profiles are used to reconstruct an image of the internal structure.
   2. **Application**: This method is commonly used in CT (Computed Tomography) scans.
6. **Type 2: Wave of Energy from Specific Spots**
   1. **Process**:
      1. A wave of energy is sent into the tissue from many specific spots.
      2. The echoes (reflected waves) from each spot are recorded.
      3. These echoes are used to reconstruct an image.
   2. **Application**: This method is typically used in ultrasound imaging.

Tomography

- all methods seen so far (sEMG, FMG/TMG, tracking) yield „surface“ information
  - what about trying to gather „deep“ information?
- we need tomography!
- in general, a method to see a slice of something you don‘t really want to slice
- more specifically, obtained by either
  - (type 1) sending a wave of energy in the tissue at many specific angles (rotating around the tissue), recording the interference profiles at the other hand and reconstructing, or
  - (type 2) sending a wave of energy in the tissue from many specific spots, recording the echos of each wave and reconstructing

1. **Attenuation**: It refers to the reduction in the intensity of the energy wave as it passes through the tissue. This reduction happens due to absorption, reflection, and scattering by the internal structures.
2. **Attenuation Profile**: For each angle from which the wave is sent, an attenuation profile is obtained, which represents how much the wave is attenuated as it passes through the tissue.

Tomography

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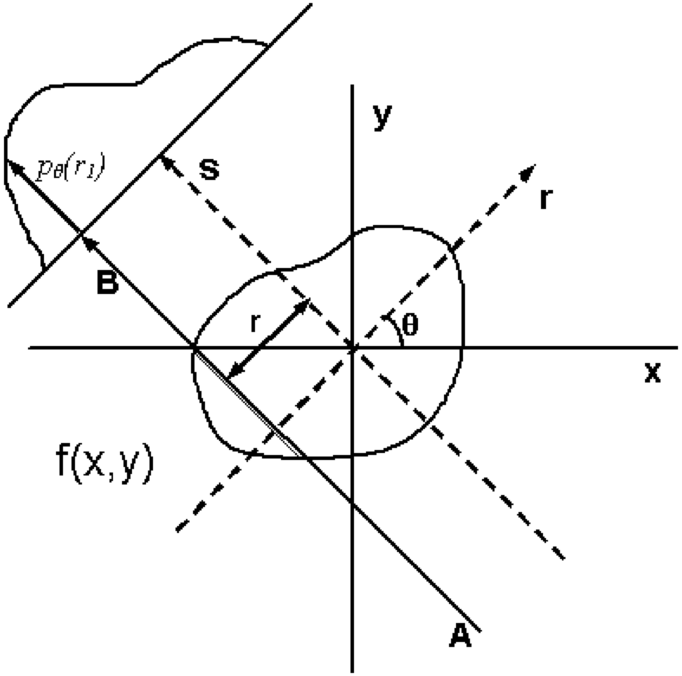
  - (type 2) sending a wave of energy in the tissue from many specific spots, recording the echos of each wave and reconstructing
- for each angle an „attenuation profile“ is obtained

$$I = I_0 \exp\left(-\int \mu(x,y)\,ds\right)$$

$$p_\theta(r) = \ln\left(\frac{I}{I_0}\right) = -\int \mu(x,y)\,ds$$



1. **Exponential Attenuation Equation**:
   - $I = I_0 \exp\left(-\int \mu(x,y)\,ds\right)$
   - Here, I is the intensity of the energy wave after it has passed through the tissue.
   - I_0 is the initial intensity of the energy wave.
   - $\mu(x,y)$ is the attenuation coefficient at a point (x,y) in the tissue.
   - The integral $\int \mu(x,y)\,ds$ represents the total attenuation along the path s that the wave travels.

2. **Logarithmic Form**:
   - $p_\theta(r) = \ln\left(\frac{I}{I_0}\right) = -\int \mu(x,y)\,ds$
   - This equation is derived from the exponential attenuation equation and provides a measure of the total attenuation along a particular path.
   - $p_\theta(r)$ represents the attenuation profile at a specific angle θ and distance r.

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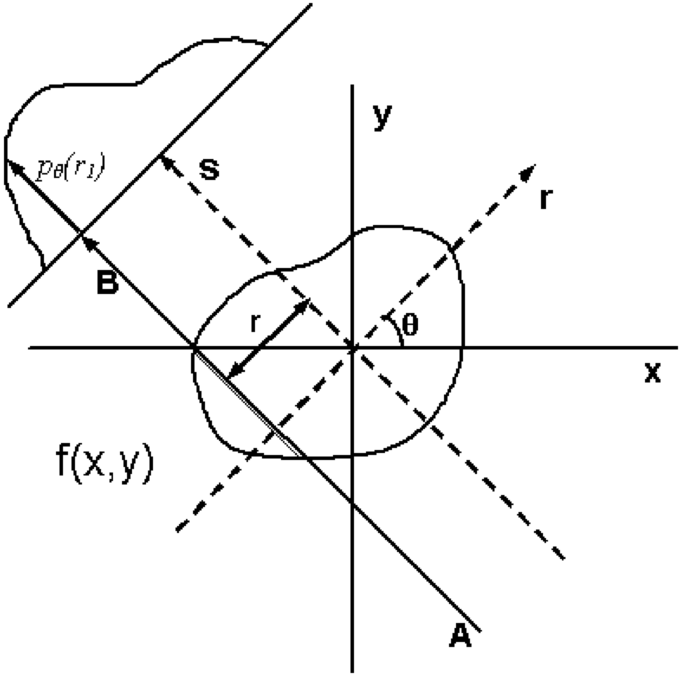
- for each angle an „attenuation profile“ is obtained

- from the complete set of attenuation profiles („sinogram“) the original image can be reconstructed

$$x\cos\theta + y\sin\theta = r$$

$$f(x,y) = \frac{1}{2\pi}\int_0^{\pi} g_\theta(x\cos\theta + y\sin\theta)\,d\theta$$



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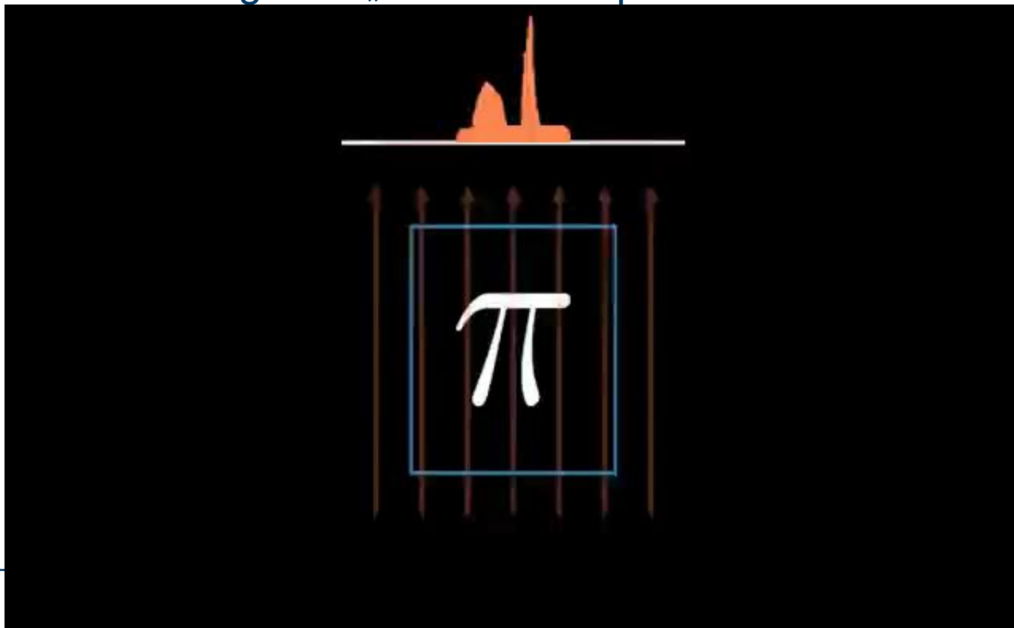
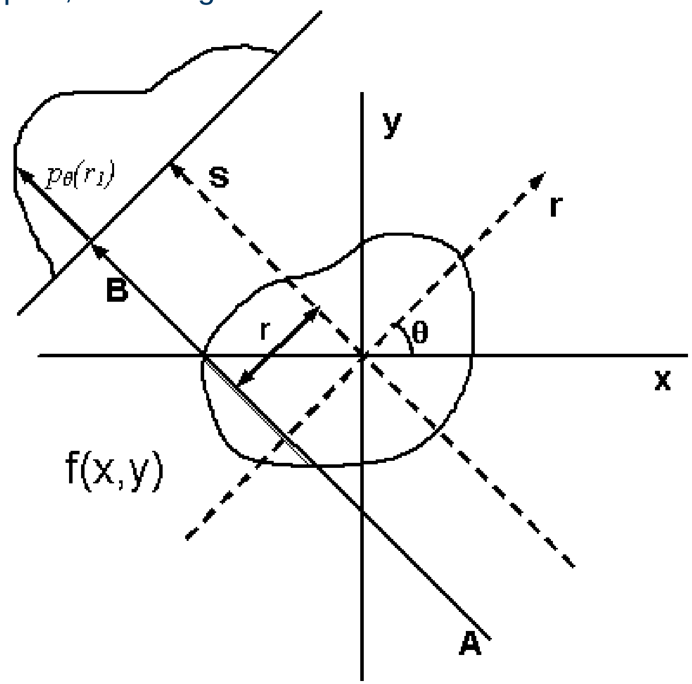
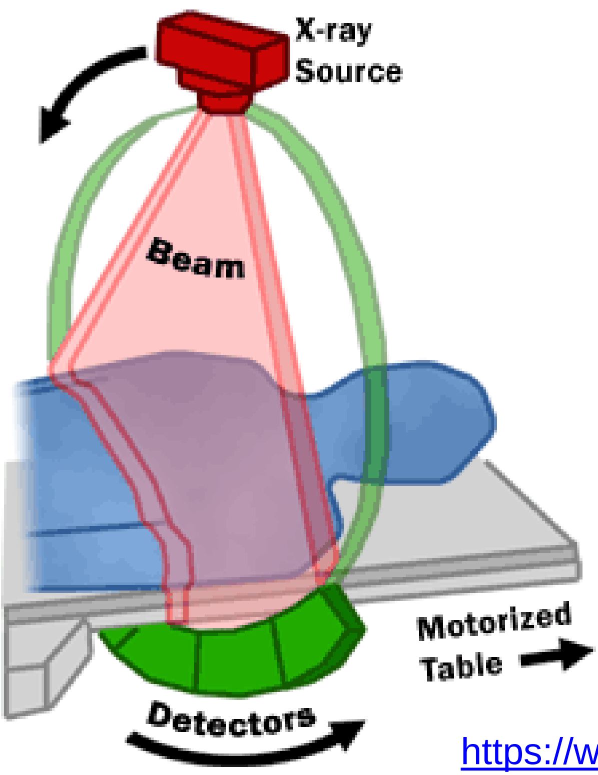
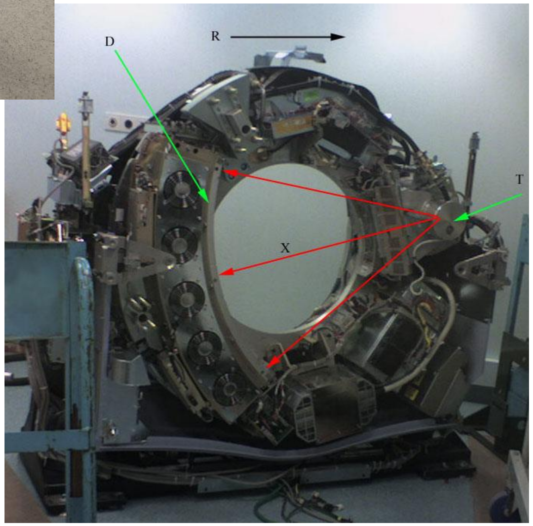




Tomography

- typical example: CT scanning





https://www.youtube.com/watch?v=gaiCtdo6CLE

Tomography

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  - **(type 2) sending a wave of energy in the tissue from many specific spots, recording the echos of each wave and reconstructing**

- source and receiver of the wave are one and the same (e.g., piezoelectric effect)
- Transducers are made of piezoelectric crystals
- so they are in the same location
- and they both send the wave and record the „echo“ of the wave
- Acoustic impedance is a property of tissue that depends on its density and the speed of sound through it

1. **High Impedance Tissues**: Bone and dense connective tissues have high acoustic impedance. When an ultrasound wave encounters these tissues, a large portion of the wave is reflected back, creating a high amplitude signal.
2. **Low Impedance Tissues**: Soft tissues like fat and muscle have lower acoustic impedance compared to bone. The reflections from these tissues are weaker, resulting in lower amplitude signals.

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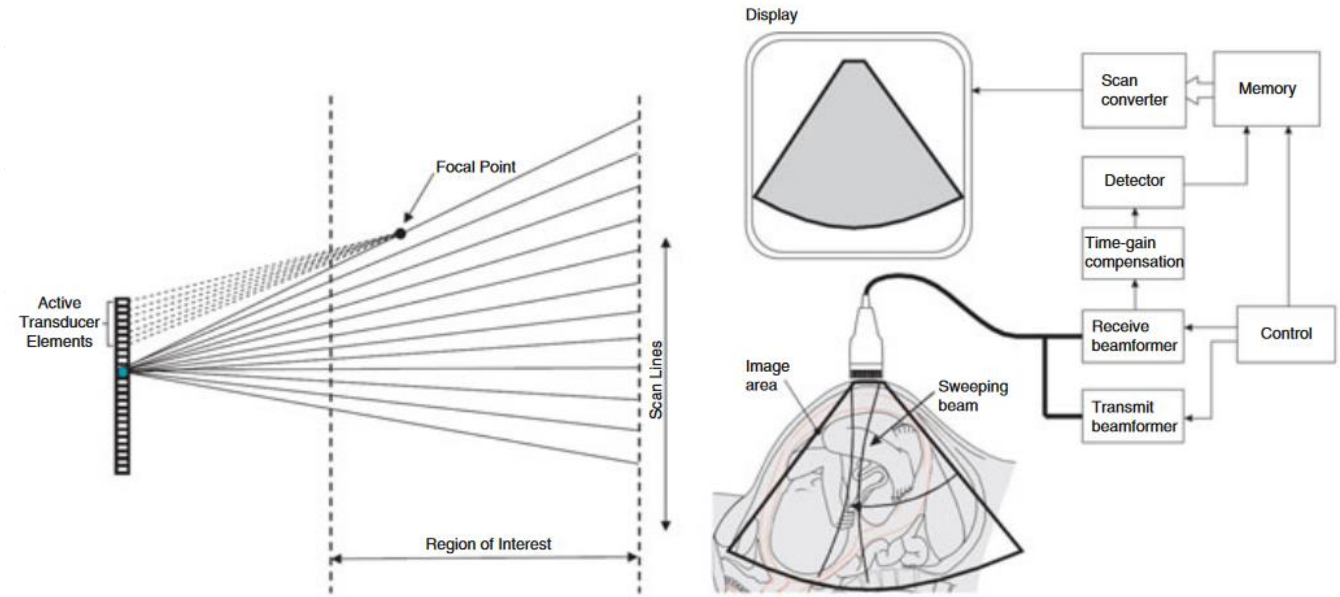

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- An echo signal from each of the transducers, P1,P2
  Amplitude difference is due to the impedence change in the tissues.

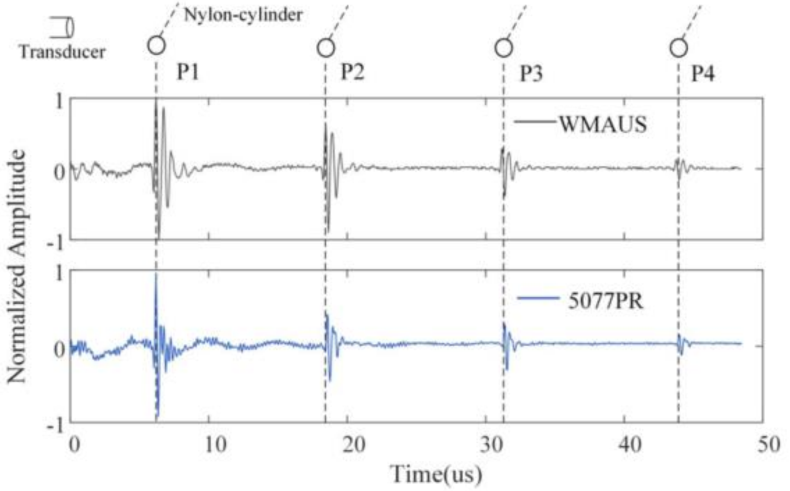


Fig. 8. Echo signals acquired from the two equipment (i.e., WMAUS and 5077PR) at the same position of the ultrasound phantom.

Electrical Impedance Tomography

(type 1)

Electrical Impedance Tomography (EIT) works by
- injecting tiny oscillating currents into the body,
- detecting the impedance at other locations of the body

- typically, a ring of electrodes (metal plates on the skin) is used to
  - inject a current through one pair of adjacent electrodes,
  - detect an impedance at all other pairs of electrodes

- the next pair is then selected for the injection
- and so on till one full round has been performed

1. **Temporal Resolution**: The frame rate (measured in frames per second, fps) indicates how quickly consecutive frames (sets of measurements) are taken. Higher frame rates allow for more rapid imaging and better temporal resolution, capturing dynamic changes within the object.
2. **Spatial Resolution**: The number of measurements within a frame (determined by the number of electrodes) impacts the spatial resolution of the reconstructed image. More measurements per frame generally lead to higher spatial resolution.

Electrical Impedance Tomography

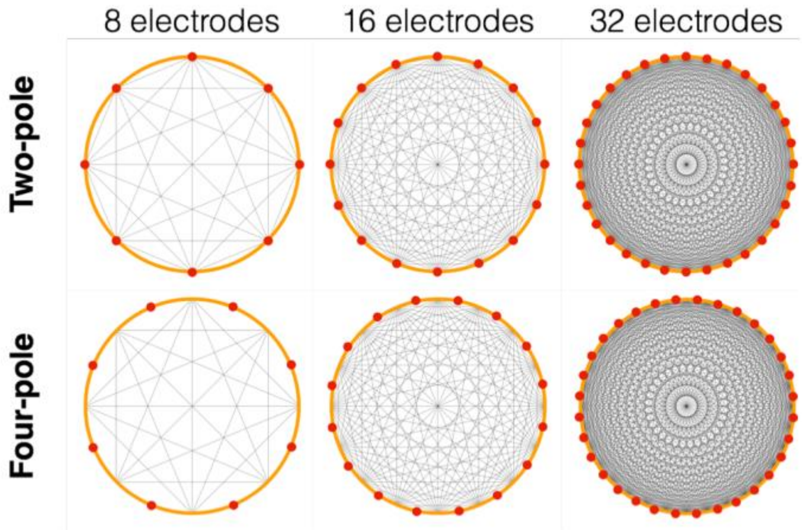


Figure 1. The number of sensed paths (grey lines) dramatically increases as electrode count grows (red dots). For reference, Tomo [43] uses a two-pole, 8-electrode scheme (upper left).

	Tomo (Two-pole)			New Setup (Two-pole)			New Setup (Four-pole)		
Number of Electrodes	8	16	32	8	16	32	8	16	32
Number of Measurements per Frame	28	120	496	28	120	496	40	208	928
Frame Rate (Hz)	10	2.3	0.6	100	22	6	87	16	3

Table 1. Performance characteristics of Tomo and our new setup. We extrapolate hypothetical performance (grey region) for 16 and 32 electrode versions of Tomo.

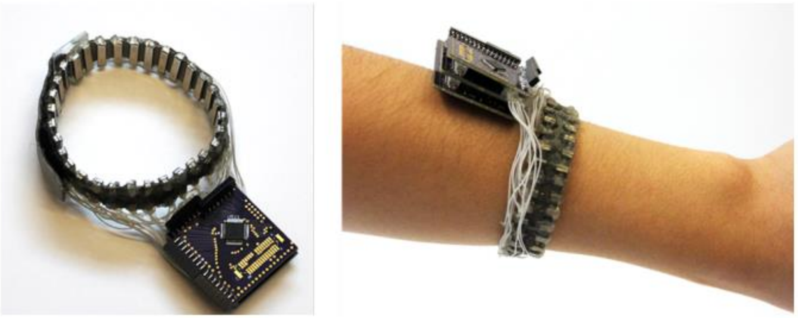


Figure 2. Our electrode band (left) and our EIT sensor worn on a user's arm (right).

Yang Zhang, Robert Xiao and Chris Harrison, Advancing Hand Gesture Recognition with High Resolution Electrical Impedance Tomography, ACM 2016

Electrical Impedance Tomography

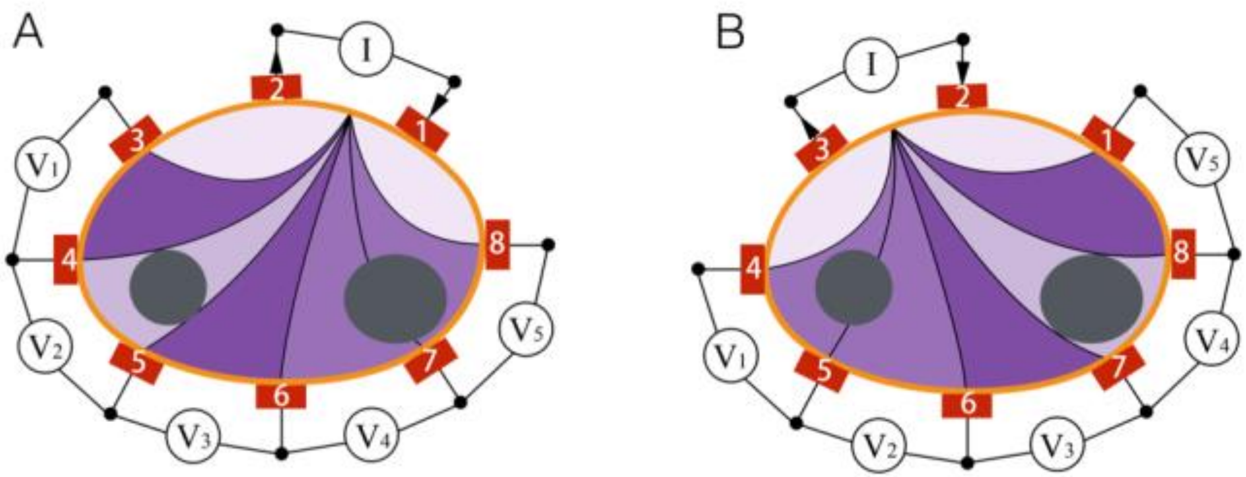


Figure 5. Two projection rounds in four-pole measurement scheme with 8 electrodes. Higher voltage difference is shown with brighter color.

Yang Zhang, Robert Xiao and Chris Harrison, Advancing Hand Gesture Recognition with High Resolution Electrical Impedance Tomography, ACM 2016

Electrical Impedance Tomography

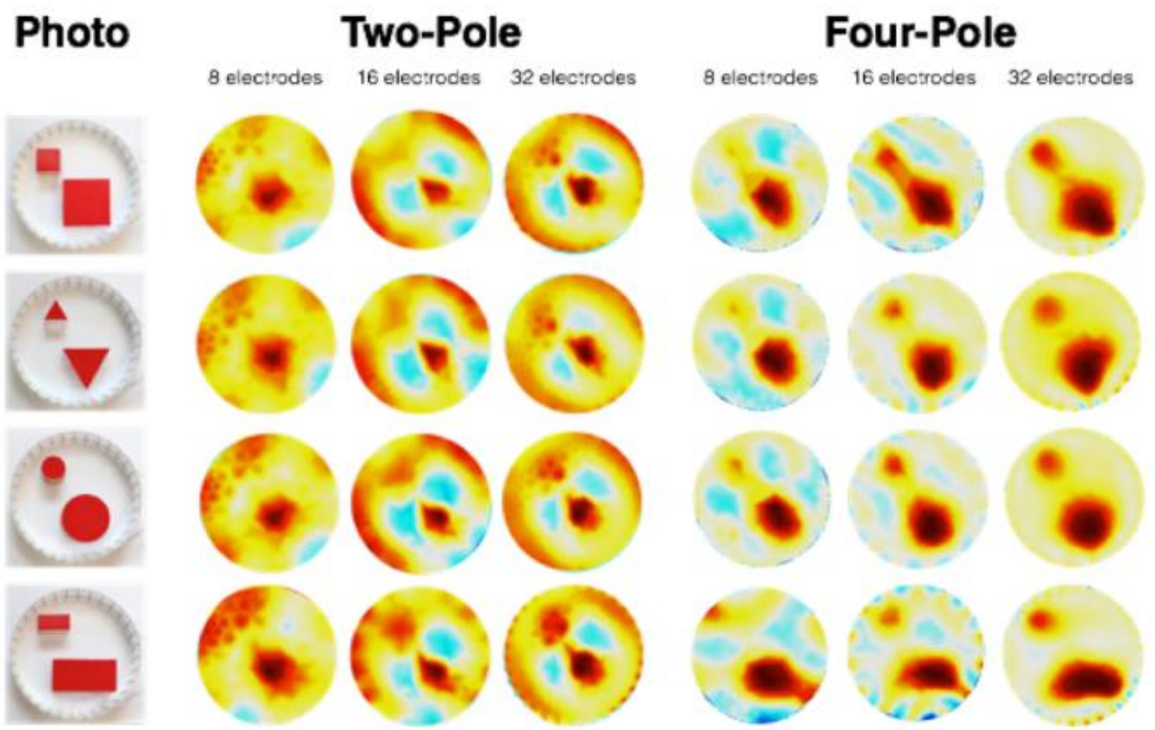


Figure 8. Reconstructed images of bath with different object shapes.

Yang Zhang, Robert Xiao and Chris Harrison, Advancing Hand Gesture Recognition with High Resolution Electrical Impedance Tomography, ACM 2016

Intent detection and somatosensory feedback

Electrical Impedance Tomography

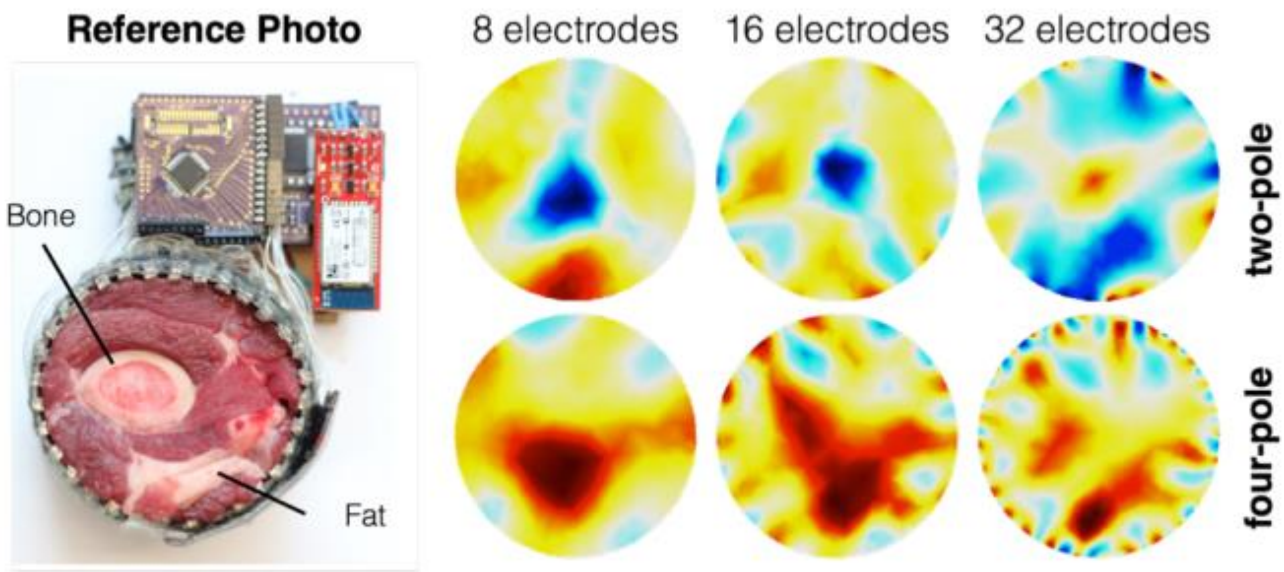


Figure 9. Reconstructed images of a cross-cut lamb shoulder with different EIT configurations.

Yang Zhang, Robert Xiao and Chris Harrison, Advancing Hand Gesture Recognition with High Resolution Electrical Impedance Tomography, ACM 2016

Electrical Impedance Tomography

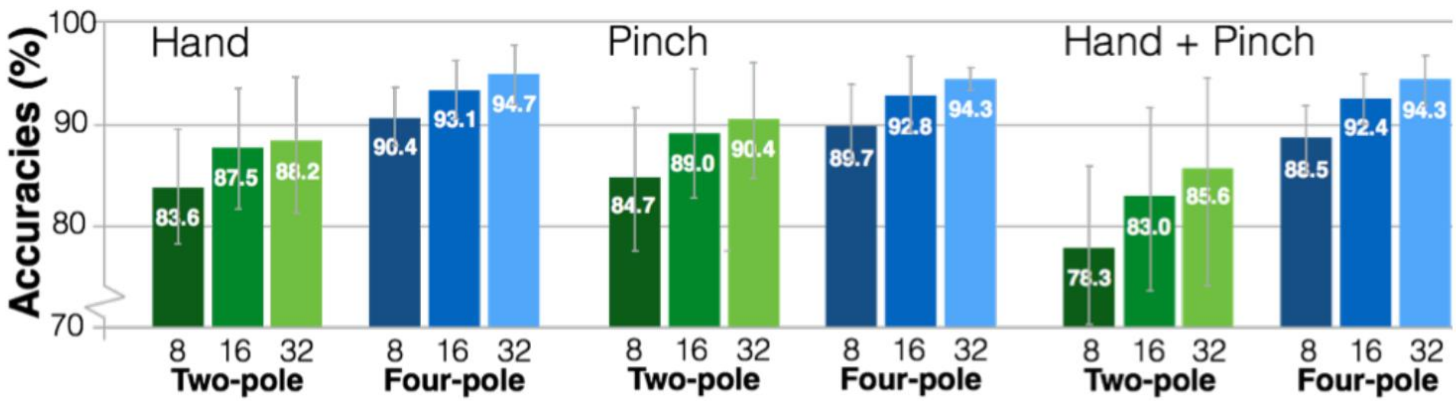


Figure 10. Accuracies for three hand gesture sets (left: Hand, middle: Pinch, right: Combined) across different EIT configurations. Numbers below bars are electrode count.

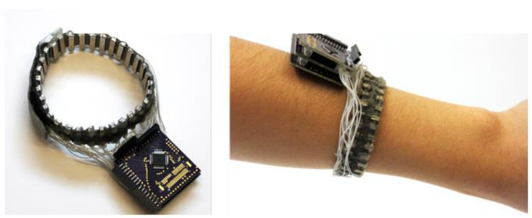


Figure 2. Our electrode band (left) and our EIT sensor worn on a user's arm (right).

Yang Zhang, Robert Xiao and Chris Harrison, Advancing Hand Gesture Recognition with High Resolution Electrical Impedance Tomography, ACM 2016

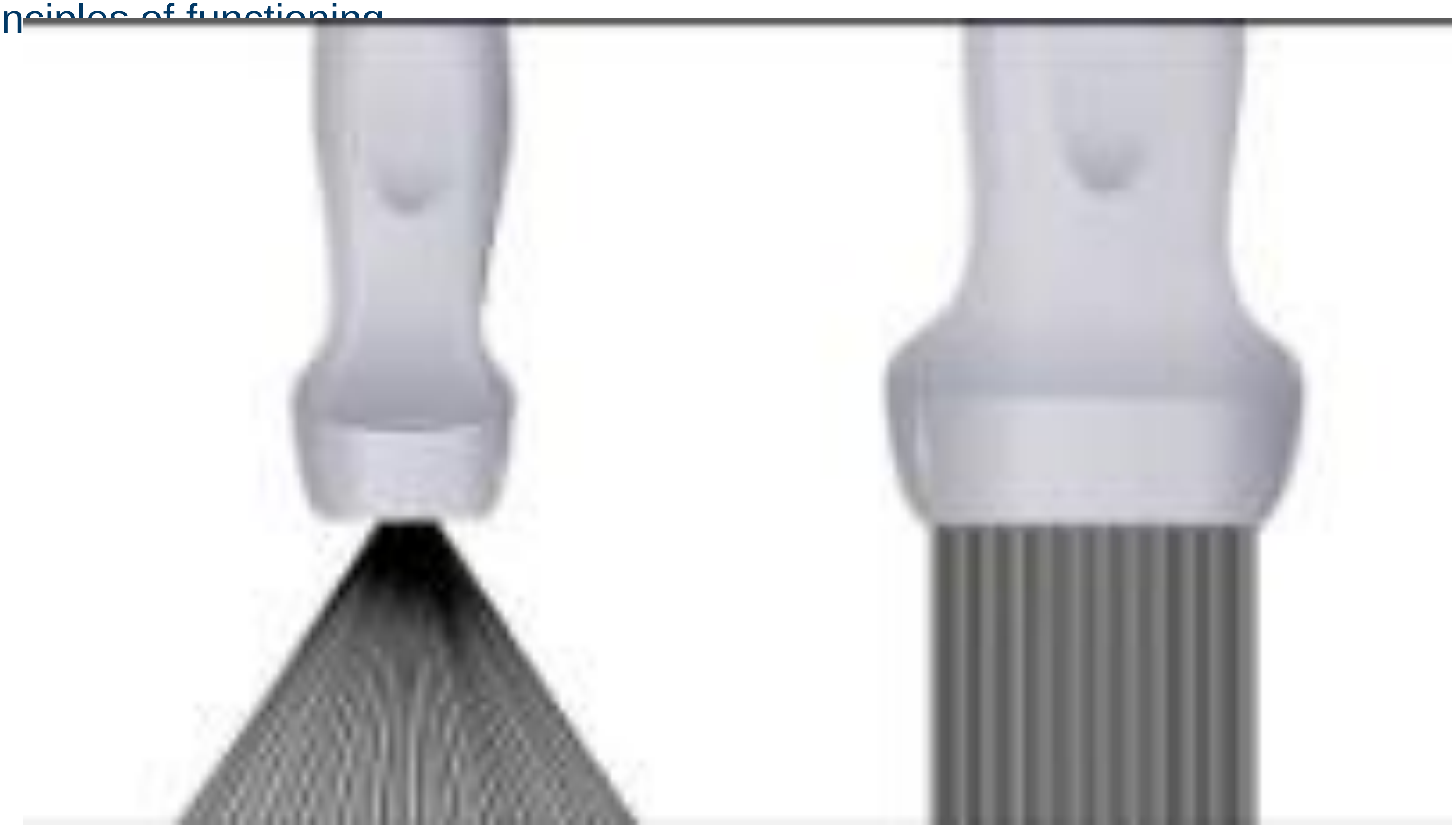
Ultrasound scanning

(type 2)

- Ultrasound (B-mode) tomography works by
  - injecting high-frequency (~10MHz) pressure waves (sound) into the body,
  - detecting the „echo“ at the same location of the body
- typically, a „transducer“ (array of ceramic piezoelectric elements) placed on the skin
  - emits a pressure wave by being electrically excited (exploit the piezo effect),
  - detects the pressure impedance change profile (exploit the same effect)
- by carefully timing the emission and detection of each transducer in the array an image can be formed (beamforming)

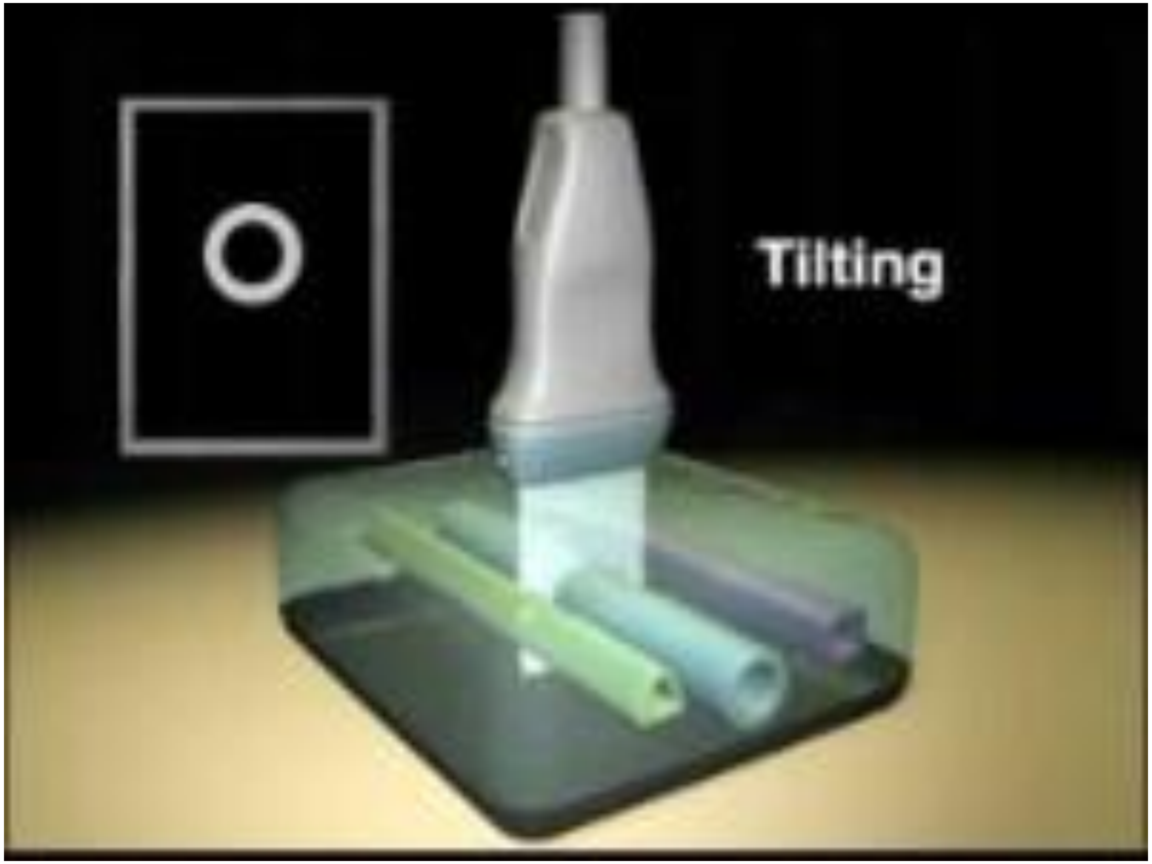
Ultrasound scanning

- principles of functioning



Ultrasound scanning

- principles of functioning



Castellini, Claudio / Passig, Georg / Zarka, Emanuel,
Using ultrasound images of the forearm to predict finger positions, 2012
IEEE Transactions on Neural Systems and Rehabilitation Engineering 20(6)

Ultrasound scanning

- so what can we see from the ultrasound scan… of the forearm?
- Used for intent detection
- Use cyberglove and ultrasound to produce training data
  Then some features are extracted from the ultrasound images
- Test – ultrasound produce images – then a virtual hand moves accroding to the y label produced from the ultrasound image
- From the image we were able to detect the pressure applied – virtual piano

Castellini, Claudio / Hertkorn, Katharina / Sagardia, Mikel / Sierra González, David / Nowak, Markus,
A virtual piano-playing environment for rehabilitation based upon ultrasound imaging,
2014, Proceedings of BioRob - IEEE International Conference on Biomedical Robotics and Biomechatronics

Ultrasound scanning

- so what can we see from the ultrasound scan… of the forearm?

Intent detection and somatosensory feedback

Xingchen Yang, Zhenfeng Chen, Nalinda Hettiarachchi, Jipeng Yan, and Honghai Liu,
A Wearable Ultrasound System for Sensing Muscular Morphological Deformations,
IEEE Transactions On Systems, Man, And Cybernetics: Systems

Ultrasound scanning

- what about miniaturisation? Need to make it smaller as possible
- possibly move from B-mode to A-mode scanning (single transducer elements)
- we use just 8 transducers – produce good results than same EMG sensors. Less transducers so that its wearable. The interface between one tissue and other as detectable via the impedenace change

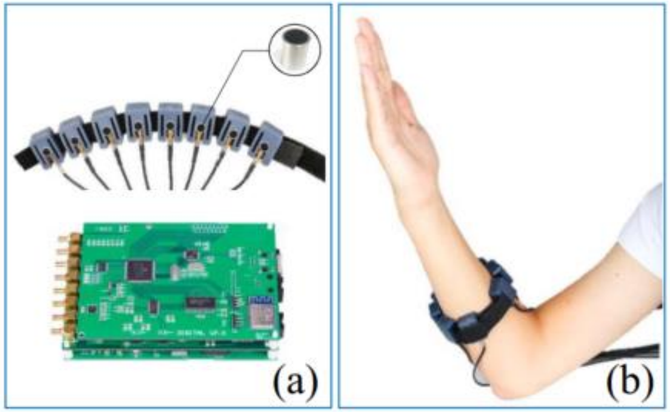


Fig. 6. Prototype of the developed ultrasound system. (a) Prototype of the customized ultrasound system, transducer, and armband. (b) Scenario of placing eight-channel transducers on the forearm.

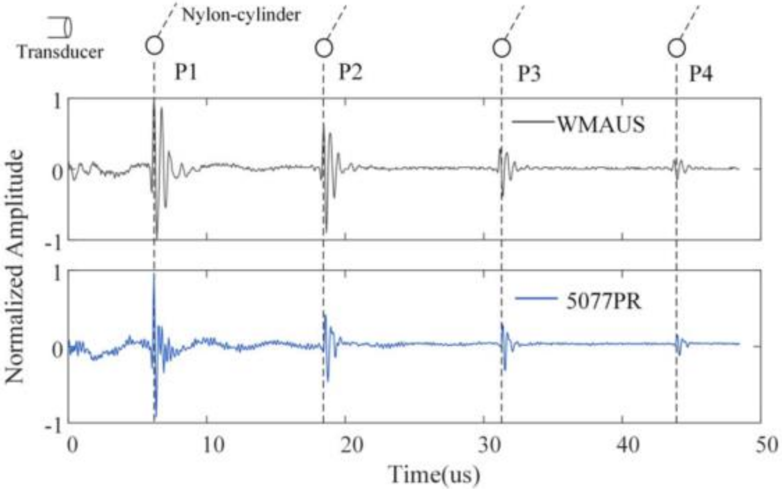


Fig. 8. Echo signals acquired from the two equipment (i.e., WMAUS and 5077PR) at the same position of the ultrasound phantom.

Intent detection and somatosensory feedback

1. **A-mode (Amplitude Mode) Scanning**:

- **Basic Principle**: A-mode ultrasound is the simplest form of ultrasound imaging. It displays the amplitude of reflected sound waves as a function of depth.
- **Display**: The output is a one-dimensional plot where the x-axis represents depth (time taken for the echo to return) and the y-axis represents the amplitude of the echo (intensity of the reflected sound wave).
- **Use Cases**: A-mode is primarily used for precise measurements of distances or thicknesses, such as in ophthalmology for measuring the length of the eye or in industrial applications.
- **Image Example**: A single spike or peak on the display represents a strong reflection from a boundary within the object being scanned.

1. **B-mode (Brightness Mode) Scanning**:

- **Basic Principle**: B-mode ultrasound provides two-dimensional images. It constructs an image by combining multiple A-mode scans taken from different angles or positions.
- **Display**: The output is a two-dimensional grayscale image where the brightness of each pixel represents the amplitude of the reflected sound wave from that particular location within the scanned plane.
- **Use Cases**: B-mode is widely used in medical imaging for visualizing soft tissue structures, such as in obstetrics for imaging fetuses, in cardiology for heart imaging, and in musculoskeletal imaging.
- **Image Example**: The result is a cross-sectional image showing various structures within the body, with different shades of gray representing different tissue densities or types.
- B-mode (Brightness mode): This is the most common mode in diagnostic ultrasound imaging. B-mode ultrasound provides a two-dimensional cross-sectional image of the tissues. The brightness of the image represents the amplitude of the reflected ultrasound waves, allowing visualization of the internal structure of organs. Each echo detected from the ultrasound pulse is represented as a dot on the screen, and the position and brightness of the dot correspond to the depth and amplitude of the echo, respectively.

- A-mode (Amplitude mode): In A-mode ultrasound, a single transducer scans a line through the body with the echoes plotted on a screen as a function of depth. This mode provides a one-dimensional image where the vertical axis represents the amplitude of the echo, and the horizontal axis represents the depth. A-mode is primarily used for ophthalmology and for measurements of distance within the body because it provides precise information about the depth of structures.

Xingchen Yang, Zhenfeng Chen, Nalinda Hettiarachchi, Jipeng Yan, and Honghai Liu,
A Wearable Ultrasound System for Sensing Muscular Morphological Deformations,
IEEE Transactions On Systems, Man, And Cybernetics: Systems, 51(6), 2021

Ultrasound scanning

- what about miniaturisation?
- possibly move from B-mode to A-mode scanning (single transducer elements)

Fig. 11. Illustration of the TAC test (Task A in Table II). The subject moved the virtual hand into the target posture using wrist supination, wrist extension, hand open and rest, where rest motion is mapped to the motion stop. The virtual hand turned green as the target was reached within acceptance tolerances (±7° for each degree of freedom). (a) Start position of the task and (b) successful completed position of the task.

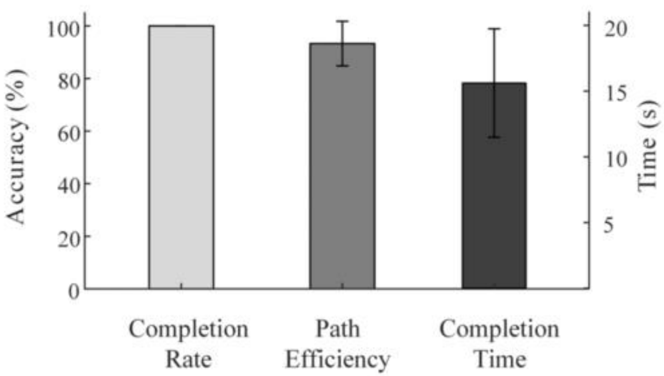
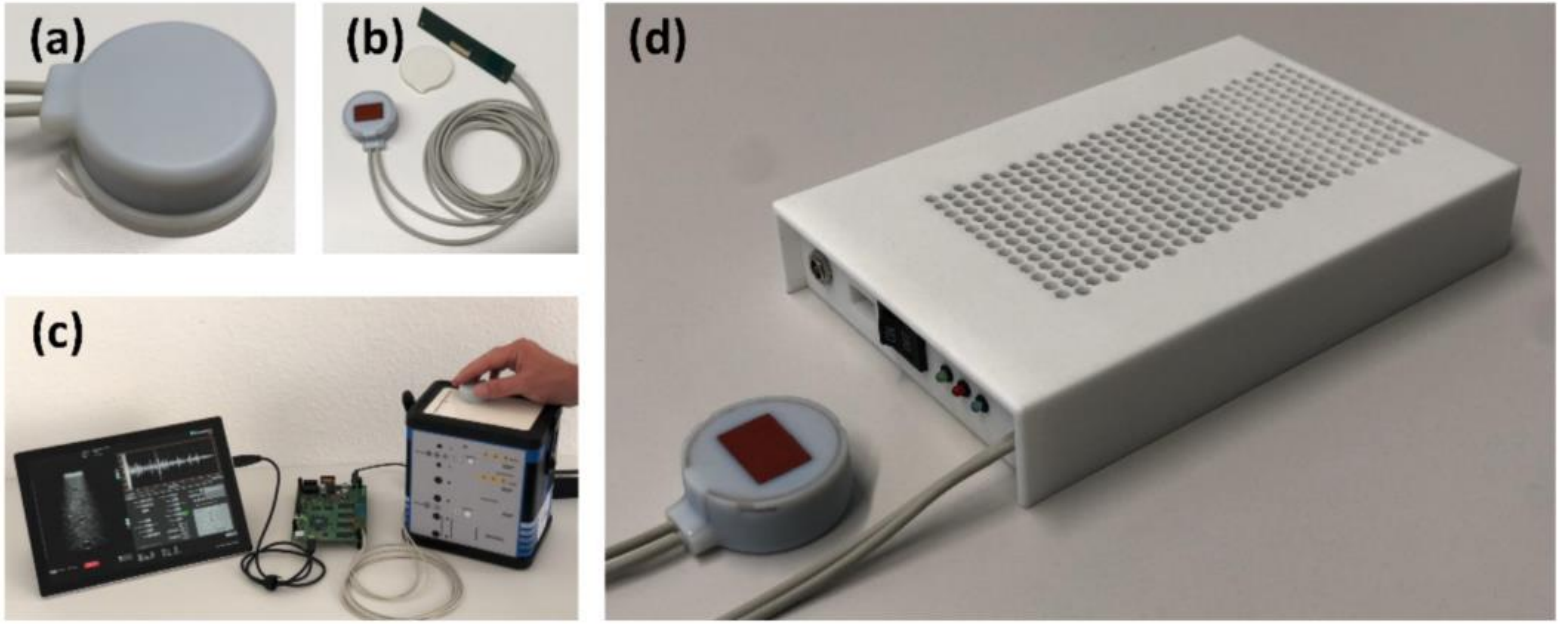


Fig. 12. Averaged performance metrics for the TAC tasks. The data is averaged across different testing trials and subjects, and the error bar denotes the standard error.

Marc Fournelle, Tobias Grün, Daniel Speicher, Steffen Weber, Mehmet Yilmaz, Dominik Schoeb, Arkadiusz Miernik, Gerd Reis, Steffen Tretbar and Holger Hewener, *Portable Ultrasound Research System for Use in Automated Bladder Monitoring with Machine-Learning-Based Segmentation*, MDPI Sensors 2021.

Ultrasound scanning

- what about miniaturisation?
- recent development:



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Ultrasound scanning

- what about miniaturisation?

- recent development:

Pros & cons

- IMUs
  - **accurate, cheap, easy to condition**
  - **need to wear (many of) them, drift**
  - **seemingly more useful in lower-limb prosthetics**
- FMG
  - **cheap, high-density, stable**
  - **prone to movement artefacts, limb position effect**
  - **features and processing unclear**
- EIT
  - **yields info about deep structures**
  - **cheap, wearable**
  - **processing unclear**
  - **minimally invasive (injection of current)**
- US
  - **extremely rich in infomation**
  - **surprisingly easy *digital* processing**
  - **not (yet) cheap at all**
  - **miniaturisation is a problem**
- sEMG
  - **cheap, high-density, stable**
  - **prone to movement artefacts, fatigue, crosstalk**
  - **features and processing defined**

Intent detection and somatosensory feedback

Chest (Torso) IMU:

1. Provides a stable global reference point.
2. Helps to isolate arm and hand movements from overall body movements.

Upper Arm IMUs:

- Capture shoulder and upper arm movements.

Forearm IMUs:

1. Capture elbow flexion/extension and forearm rotations.
2. Example: IMUs mounted on the forearm, near the midpoint between the wrist and elbow.

Hand/Wrist IMUs:

1. Capture wrist and hand movements.
2. Inaccurate Positioning:
3. Loss of Precision:
4. Unstable Control

- The robots might crash into each other
- There will be an increasing shift in the direction of the drift
- Even if the user does not move, the robots will move

Summary

- today:
  - muscle activity – detecting deformations induced by it
  - via tomography – yields „deep“ information
  - via EIT and ultrasound tomography and A-mode scanning

- results?
  - extremely interesting but so far impracticable (not for very much longer…)
  - hasn‘t been used at all in the clinics so far

References

- Yang Zhang, Robert Xiao and Chris Harrison, Advancing Hand Gesture Recognition with High Resolution Electrical Impedance Tomography, ACM 2016
- Castellini, Claudio / Passig, Georg / Zarka, Emanuel, Using ultrasound images of the forearm to predict finger positions, 2012, IEEE Transactions on Neural Systems and Rehabilitation Engineering 20(6)
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