Rank determination for figure 22 in "Nondestructive Evaluation of Material Properties in Polymer Additive Manufacturing Processes: Moving Towards Process-agnostic Qualification"

The ranking is on a scale of 1 to 5. Lowest values are the best values. We looked at 3 categories: measurement, accessibility, and equipment cost. Below are the justifications for all of the categories:

Ranking Scale for Measurement:

- **1:** Simple conversion from the signal to a measurement.
- **2:** Basic calibration needed and minimal analysis required.
- **3:** Requires calibration or alignment. Requires some software to get a measurement.
- **4:** Requires extensive calibration or alignment. Requires custom/advanced codes or advanced computational resources to obtain the measurement. Requires training.
- **5:** Requires a specialist to run/maintain the machine and obtain results.

Measurement Rankings:

1. **Thermocouple: 1**
    - *Reasoning:* Direct voltage to temperature conversion with proper calibration. Most applications (especially for the lower temperatures in polymer AM) only need simple physical integration. Conversion is widely understood and does not require extensive expertise.
2. **IR Camera: 2**
    - *Reasoning:* Emissivity calibration needed for quantitative analysis. Software is typically required to obtain thermal measurements. Point measurements are simple, but 2D data can become more complex to analyze. Mitigation of thermal reflections is needed in some cases.
3. **IR Sensor: 2**
    - *Reasoning:* Involves signal processing to convert to a temperature measurement. Relatively easy to integrate the sensor into the workflow. Mitigation of thermal reflections is needed in some cases.
4. **Pressure Transducer: 1**
    - *Reasoning:* Direct voltage to pressure conversion with proper calibration. Pressure is directly relevant to capillary flow and therefore polymer viscosity and shear rate measurements. Physical integration is typically straightforward, although it sometimes requires specialized designs for integration.
5. **Force Transducer**: **2**
    - *Reasoning:* Although the conversion from a voltage to a force is direct, conversion to a relevant polymer processing condition, such as shear rate, is less direct.

6. **Rotary encoder: 2**
    - *Reasoning:* Although the conversion from a numerical measurement to angular position is direct, conversion to a relevant polymer processing condition is less direct. For example, angular velocity can be related to a filament feed rate, but does not allow direct conversion to relevant processing conditions or polymer properties like shear rate or viscosity. Angular acceleration and velocity must be calculated.
7. **Self-sensing Materials: 2**
    - *Reasoning:* Using basic probes to measure electrical conductivity in self-sensing materials allows for easy qualitative measurements. However, quantitative measurements require calibration. Conversion to material properties (i.e. strains and deformations) are highly dependent on the calibration. For most short term applications and a fixed geometry, calibrations and measurements are not overly complex. However, we acknowledge that in more specialized and long term cases, the calibration is sensitive to material geometry, stability of the electrically conductive additives/polymer, temperature, humidity, etc.
8. **PZT Sensor: 2**
    - *Reasoning:* Operation and integration of PZT sensors is relatively straightforward. However, interpreting electrical impedance measurements requires analysis. Calibrating impedance responses to material properties is needed for quantitative analysis.
9. **Electrical Impedance Tomography (EIT): 4**
    - *Reasoning:* Requires careful electrode placement and contact. Data acquisition involves injecting currents and measuring voltages across many electrode combinations. Solving the inverse problem requires sophisticated, iterative reconstruction algorithms and specialized software. Requires significant training and expertise.
10. **Accelerometer: 2**
    - *Reasoning:* Basic calibration is often needed. The signal is directly related to acceleration measurements. Although vibrations affect the quality of a print, it is unclear how accelerometer readings directly give relevant processing or polymer properties.
11. **Laser Doppler Vibrometry (LDV): 3**
    - *Reasoning:* Requires careful alignment of the laser beam. Software is needed to process the Doppler shift and to convert it into a velocity. Therefore, the velocity of a polymer in a flowing state can be measured, which is relevant to viscosity for example. Training is generally required for proper setup.
12. **Acoustic Emission (AE) Sensor: 3**
    - *Reasoning:* Conversion of electrical signals to acoustic waves is achieved with signal processing. Direct understanding of how acoustic signals convert to relevant processing conditions and polymer properties is less straightforward.
13. **Ultrasound: 3**
    - *Reasoning:* Requires contact medium and proper probe placement. Interpretation of scans requires training. Software is essential for image formation and basic measurements. Conversion to viscoelastic properties requires correct models.
14. **Visible Imaging: 1**

- *Reasoning:* Basic image capture requires no special analysis beyond viewing the image. Image processing/analysis can accompany visible imaging to increase the measurement complexity. However, many algorithms, such as particle tracking or particle size measurement, are standardized and available in open source software, making it easy to implement without extensive experience.

15. **Digital Image Correlation (DIC): 3**
    - *Reasoning:* Requires meticulous application of a speckle pattern to the imaged surface. Careful camera calibration is essential for accurate quantitative measurements. Computationally intensive algorithms are used to track speckles and calculate displacement/strain fields, often requiring specialized software and training.
16. **Schlieren: 3**
    - *Reasoning:* Requires precise alignment of light sources, lenses/mirrors, knife edge, and camera. Typically requires training to operate and measure density gradients.
17. **Light Scattering: 4**
    - *Reasoning:* Requires careful alignment of the laser and detector. Data analysis involves complex models that require specialized software and expertise in light scattering principles.
18. **Optical Scattering Tomography (OST): 4**
    - *Reasoning:* OST is a specialized technique used in few research papers, but is based on Optical Projection Tomography (OPT). Therefore, this ranking is based on OPT. Requires acquisition of many 2D projections from different angles, and computationally intensive 3D reconstruction algorithms. Calibration for optical distortions is often needed. Requires specialized software and training.
19. **Optical Coherence Tomography (OCT): 4**
    - *Reasoning:* Requires highly specialized software for volumetric reconstruction and quantitative analysis of scattering properties. Requires specialized training.
20. **Raman Spectroscopy: 3**
    - *Reasoning:* Requires calibration with known standards. Data acquisition involves laser calibration. Analysis requires specialized software and training to extract chemical information from polymers. It also requires knowledge of which chemical bonds to measure and how that relates to polymer composition.
21. **Optical Microscopy: 1**
    - *Reasoning:* Basic imaging of a sample is straightforward, although adjustment of focus and lighting is typically needed to collect high-resolution images. Further image analysis, such as particle size imaging, can be achieved with well documented open source codes.
22. **Optical Profilometry: 3**
    - *Reasoning:* Sample preparation is straightforward, unless a coating is needed to image a transparent surface. Software is essential for reconstructing the 3D surface profile and performing metrological analysis. Proper interpretation of the surface requires training and expertise.
23. **Synchrotron X-ray: 5**

    - *Reasoning:* Complex optics alignment, specialized detectors, and operation procedures are required for high quality in-situ polymer data. Experts are required to operate the machines and to conduct highly specialized analysis.

24. **X-ray Micro-CT: 4**
    - *Reasoning:* Requires careful selection of X-ray parameters and mitigation of artifacts, such as beam hardening, to obtain meaningful results. Requires computationally intensive 3D reconstruction software. Often involves advanced postprocessing for segmentation and quantitative analysis. Training is needed for operation and interpretation of results.
25. **X-ray Diffraction (XRD): 4**
    - *Reasoning:* Requires precise sample preparation of powders or thin films. Data analysis involves peak identification, which requires specialized software expertise in crystallography.

Ranking Scale for Accessibility:

- **1:** Present in almost every lab at an institution.
- **2:** Present in many labs at an institution but not all.
- **3:** Available in a user facility (e.g., core facility, shared departmental lab).
- **4:** Only one machine is available at an institution (or very few across campus).
- **5:** Only a few machines in the world (requires traveling to a national/international facility).

Accessibility Rankings:

1. **Thermocouple: 1**
    - *Reasoning:* The most common temperature measurement across virtually all scientific and engineering disciplines. Most student engineering organizations have access.
2. **IR Camera: 2**
    - *Reasoning:* Basic thermal cameras are common in many facilities or laboratories. Collaboration might be required to access more specialized thermal cameras.
3. **IR Sensor: 1**
    - *Reasoning:* Basic IR sensors are common in many facilities or laboratories.
4. **Pressure Sensor: 1**
    - *Reasoning:* Found in laboratories dealing with fluids, gases, or capillary rheometry.
5. **Force Transducer**: **1**
    - *Reasoning:* Found in laboratories dealing with machinery and mechanics. Most student engineering organizations have access.

6. **Rotary encoder: 1**
    - *Reasoning:* Found in many laboratories dealing with manufacturing and robotics. Most student engineering organizations have access.
7. **Self-sensing Materials: 1**
    - *Reasoning:* While most laboratories are not directly using self-sensing materials for their intended use, many researchers commonly make polymeric materials with electrically conductive additives (i.e. carbon fiber/nanotubes, metals, etc.). Furthermore, almost all laboratories have electrical probe devices. So, although not used intentionally, the elements are currently available in many laboratories.
8. **PZT Sensor: 1**
    - *Reasoning:* PZT sensors are piezoelectric, which broadens their use in many laboratories, such as acoustics and vibrations.
9. **Electrical Impedance Tomography (EIT): 4**
    - *Reasoning:* These are highly specialized machines that are likely found in a very few biomedical engineering or electrical engineering research groups at an institution.
10. **Accelerometer: 1**
    - *Reasoning:* Due to their use in obtaining vibration measurements, they are present in many mechanical, civil, aerospace, and even some biomedical labs. Most student engineering organizations have access.
11. **Laser Doppler Vibrometry (LDV): 3**
    - *Reasoning:* It is a specialized setup that is likely found in dedicated acoustics, dynamics, or metrology labs.
12. **Acoustic Emission (AE) sensor**: **2**
    - *Reasoning:* It is commonly found in acoustics or dynamics laboratories, but also in other broader engineering laboratories.
13. **Ultrasound: 2**
    - *Reasoning:* It is widely available in many biomedical, clinical, and materials testing labs.
14. **Visible Imaging: 1**
    - *Reasoning:* It is one of the most common measurement techniques available in every laboratory when considering basic resolutions and frame rates. Most student engineering organizations have access. More specialized cameras (high-speed, high-resolution) are less common and likely require collaboration for use.
15. **Digital Image Correlation (DIC): 3**
    - *Reasoning:* Requires high-speed and high-resolution cameras and dedicated software. While growing in popularity, DIC is typically found in solid mechanics labs, materials testing facilities, or engineering core facilities.
16. **Schlieren: 4**
    - *Reasoning:* It requires a dedicated optics table and significant space to operate. It is present in a few fluid dynamics or combustion laboratories.
17. **Light Scattering: 3**
    - *Reasoning:* Commercial versions are commonly used in chemistry, biology, and materials science departments. They are often housed in a shared analytical instrument lab or core facility. However, custom set ups are present in very few laboratories.

18. **Optical Scattering Tomography (OST): 4**
    - *Reasoning:* OST is a specialized technique used in few research papers, but is based on Optical Projection Tomography (OPT). Therefore, this ranking is based on OPT. An institution might have one or two biology laboratories with this specialized equipment.
19. **Optical Coherence Tomography (OCT): 3**
    - *Reasoning:* Tends to be a share resource in biomedical engineering, ophthalmology, and clinical research labs.
20. **Raman Spectroscopy: 2**
    - *Reasoning:* A very common technique present in many chemistry, materials science, and physics departments, often as a shared instrument.
21. **Optical Microscopy: 1**
    - *Reasoning:* Although more specialized microscopes are less common, the existence of portable USB optical microscopes now makes optical microscopy fairly common in biological, chemical, and materials science laboratories.
22. **Optical Profilometry: 3**
    - *Reasoning:* Typically found in metrology labs or characterization core facilities.
23. **Synchrotron X-ray: 5**
    - *Reasoning:* Only a few exist globally. Access is restricted and only granted through a competitive proposal process.
24. **X-ray Micro-CT: 3**
    - *Reasoning:* Common in materials science and biomedical characterization facilities.
25. **X-ray Diffraction (XRD): 3**
    - *Reasoning:* Common in materials science and chemistry characterization facilities.

Ranking Scale for Cost:

- **1:** <$10,000 equipment cost
- **2:** $10,000-$100,000 equipment cost
- **3:** $100,000-$500,000 equipment cost
- **4:** $500,000-$1,000,000 equipment cost
- **5:** >$1,000,000 equipment cost

Cost Rankings:

1. **Thermocouple: 1**
    - *Reasoning:* A single thermocouple probe usually costs about tens of dollars. A multi-channel data acquisition system can be purchased under $10,000.
2. **IR Camera: 1 and 2**

   - *Reasoning:* Basic handheld cameras cost about a few hundred dollars. Specialized IR cameras tend to be in the tens of thousands range depending on the resolution and frame rate.
3. **IR Sensor: 1**
   - *Reasoning:* Basic handheld cameras cost about a few hundred dollars. Specialized IR cameras tend to be in the tens of thousands range depending on the resolution and frame rate.
4. **Pressure Sensor: 1**
   - *Reasoning:* A pressure sensor usually costs about a few hundred dollars. A multi-channel data acquisition system can be purchased under $10,000.
5. **Force Transducer**: **1**
   - *Reasoning:* A force transducer usually costs about a few hundred dollars. A multi-channel data acquisition system can be purchased under $10,000.
6. **Rotary Encoder**: **1**
   - *Reasoning:* Rotary encoders can cost anything from tens of dollars to a few hundred dollars.
7. **Self-sensing Materials: 1**
   - *Reasoning:* Basic handheld meters required to measure electrical conductivity cost about a few hundred dollars. Laboratory grade benchtop meters are typically a few thousand dollars. Electrodes cost under $100.
8. **PZT Sensors: 1**
   - *Reasoning:* Basic meters required to measure the signal typically cost a few hundred to a few thousand dollars. Precision impedance analyzers cost about a few thousand dollars. In some specialized cases, they can exceed $10,000, but this is not typical. The sensors themselves cost no more than a few hundred dollars, and many options are under $100.
9. **Electrical Impedance Tomography (EIT): 1, 2, and 3**
   - *Reasoning:* Custom research systems using basic components can be <$10,000. However, commercial systems can cost anything from tens of thousands of dollars to a few hundred thousand dollars.
10. **Accelerometer: 1**
    - *Reasoning:* Individual accelerometers are usually hundreds of dollars to a few thousand dollars. Electrical boards like an Arduino or Raspberry Pi can be purchased for under $10,000.
11. **Laser Doppler Vibrometry (LDV): 1 and 2**
    - *Reasoning:* Some portable LDV systems cost less than $10,000, while more advanced systems are in the tens of thousands of dollars range. This is largely dictated by whether it is a single point or scanning system.
12. **Acoustic Emission (AE) Sensor: 1 and 2**
    - *Reasoning:* The sensors can cost a few hundred dollars to a few thousand dollars. The signal processor can also cost a few hundred dollars to several thousand dollars.
13. **Ultrasound: 1, 2, and 3**
    - *Reasoning:* Portable diagnostic ultrasound machines can cost a few thousand dollars. Typical systems cost tens of thousands of dollars. Some clinical grade systems can cost over $100,000.

14. **Visible Light Cameras: 1 and 2**
    - *Reasoning:* A basic camera can be a few hundred dollars to a few thousand dollars. High-speed cameras can easily range from $10,000 to $100,000. Some cameras can exceed this price, but the frames rates in those cameras far exceed the speed of any visibly observable polymer dynamics in the AM process.
15. **Digital Image Correlation (DIC): 1 and 2**
    - *Reasoning:* A complete DIC system requires cameras, lighting, and software. On the low resolution and low frame rate end, it is possible to set up basic DIC for less than $10,000. However, it is more typical to use high-speed, high-resolution cameras, which puts the price around tens of thousands of dollars.
16. **Schlieren: 1 and 2**
    - *Reasoning:* A basic Schlieren system with off the shelf optics and a cheap camera can be assembled for a few thousand dollars. More advanced systems with precision optics and high-speed cameras cost tens of thousands of dollars.
17. **Light Scattering: 1 and 2**
    - *Reasoning:* Lab built systems with a cheap laser and optics can be built under $10,000. Commercial light scattering systems cost tens of thousands of dollars, depending on features.
18. **Optical Scattering Tomography (OST): 1 and 2**
    - *Reasoning:* OST is a specialized technique used in few research papers, but is based on Optical Projection Tomography (OPT). Therefore, this ranking is based on OPT. Custom systems range from a few thousand to tens of thousands of dollars.
19. **Optical Coherence Tomography (OCT): 2 and 3**
    - *Reasoning:* Basic research or used clinical systems cost tens of thousands of dollars. New systems cost a few hundred thousand dollars.
20. **Raman Spectroscopy: 2 and 3**
    - *Reasoning:* Benchtop or portable Raman systems are in the tens of thousands of dollars range. Advanced systems can easily reach a few hundred thousand dollars.
21. **Optical Microscopy: 1 and 2**
    - *Reasoning:* Basic student and USB microscopes can cost a few hundred dollars to a few thousand dollars. Research microscopes cost tens of thousands of dollars.
22. **Optical Profilometry: 1 and 2**
    - *Reasoning:* Handheld scanners with adequate resolution typically cost a few thousand dollars. Stationary, specialized profilometers cost tens of thousands of dollars depending on resolution.
23. **Synchrotron X-ray: 5**
    - *Reasoning:* Construction and operation costs for a synchrotron facility are in the hundreds of millions to billions of dollars.
24. **X-ray Micro-CT: 3 and 4**
    - *Reasoning:* Laboratory micro-CT systems typically ranging from a few hundred thousand dollars to over $500,000 depending on resolution, power, and features.
25. **X-ray Diffraction (XRD): 2 and 3**
    - *Reasoning:* Basic powder XRD systems can cost tens of thousands of dollars. Advanced systems can easily cost a few hundred thousand dollars.