**Test Case: Digitizing a Semi Robotic Line Boring Machine for 3D Motion Capture**

**1. Introduction**

The line boring machine (portable lathe) and bore welding machine used in this test case are **semi-robotic systems**, capable of programmable operation. These machines perform precision cutting and rotational welding, making them ideal candidates for **Digital Twin integration**. The ability to program motion and automate machining sequences provides an opportunity to enhance **real-time monitoring, accuracy validation, and performance optimization** through **sensor-based digitization**.

Digitizing a **line boring machine (portable lathe)** requires integrating **sensors, data acquisition systems, and a Digital Twin** to capture real-time **3D motion, forces, and operational parameters**. This test case defines the necessary **hardware, software, and manufacturing equipment** for successful implementation.

**1.1 Objectives**

* Develop a **Digital Twin** of the line boring machine for **real-time monitoring and optimization**.
* Capture **3D motion, force, vibration, and spindle behavior**.
* Evaluate the effectiveness of **sensor integration for predictive maintenance**.
* Establish a **data acquisition pipeline** for Digital Twin integration.

**2. System Components**

**2.1 Hardware: Sensors & Data Collection**

| **Component** | **Purpose** | **Estimated Cost** |
| --- | --- | --- |
| **IMU (Inertial Measurement Unit)** | Captures motion in 6-DOF | $200 - $1,000 |
| **Laser Displacement Sensor** | Measures tool and workpiece positioning | $1,500 - $5,000 |
| **Rotary Encoders** | Tracks spindle & feed rate | $300 - $1,200 |
| **Strain Gauges** | Monitors stress and force on machine frame | $50 - $500 |
| **Force/Torque Sensors** | Measures cutting forces | $2,000 - $10,000 |
| **Vibration Sensors (Accelerometers)** | Detects wear and imbalance | $500 - $2,500 |
| **Temperature Sensors (Thermocouples)** | Monitors machine and tool heat | $100 - $500 |
| **Data Acquisition System (DAQ)** | Captures sensor data | $2,500 - $15,000 |
| **Edge Computing Device** | Processes real-time data | $500 - $5,000 |

**Budget Option: Off-Brand Alternatives**

* **IMU Sensors**: Instead of high-end Bosch or VectorNav IMUs ($500 - $1,000), consider **MPU6050 or BNO055 Arduino-compatible IMUs** (~$50 - $100). These provide reasonable **6-DOF motion tracking** for prototype testing.
* **Rotary Encoders**: Use **generic optical encoders** ($800 - $1,200).
* **Data Acquisition (DAQ) System**: Raspberry Pi or Arduino-based **DAQ modules** (~$300) can be used instead of National Instruments (NI) DAQs ($2,500 - $15,000). While lacking high-speed sampling, they are sufficient for basic motion tracking.
* **Force & Torque Sensors**: Consider **strain gauge-based DIY load sensors** (~$200) instead of ATI or Kistler sensors ($2,000+). These require additional signal processing but are cost-effective.

**Budget Option: DIY 3D Printing Solutions**

* **3D Printer for Sensor Mounts**: Instead of industrial **Stratasys or Markforged printers** ($10,000+), consider **Creality Ender 3 or Prusa i3 MK3** (~$500 - $1,200) for fabricating plastic sensor mounts.
* **Metal 3D Printing Alternative**: Instead of a $30,000+ metal 3D printer, consider **hybrid solutions**:
  + Print in **PLA or ABS** and reinforce with **epoxy or carbon fiber**.
  + Use **lost-wax casting** or **CNC machining** for final metal parts.
* **Entry-Level CNC Machines**: Instead of Haas VF-2 ($10,000) or **Shapeoko CNC routers** (~$2,000) for basic milling and sensor housing modifications.
* **Off-brand alternatives** such as Arduino-compatible IMUs ($150), and Raspberry Pi-based DAQ systems (~$300) can be used initially.

**2.2 Software: Digital Twin & Data Processing**

| **Software** | **Purpose** | **Estimated Cost** |
| --- | --- | --- |
| **Siemens NX** | Digital Twin modeling & simulation | $3,000+ (per year) |
| **PTC Creo** | Machine kinematics & system modeling | $2,500+ (per year) |
| **MATLAB/Simulink** | Data processing & predictive analytics | $1,000+ (license) |
| **LabVIEW (NI)** | Sensor data acquisition & real-time monitoring | $2,500+ |
| **ThingWorx (PTC)** | IoT-based real-time monitoring | $5,000+ (enterprise) |

**Budget Option:**

* **Free/Open-Source Alternatives**: Free CAD, Open Modelica, and Python (SciPy + Pandas) for data analytics.

**2.3 Manufacturing Equipment**

| **Machine Type** | **Purpose** | **Estimated Cost** |
| --- | --- | --- |
| **CNC Milling Machine** | Fabricate sensor mounts & brackets | $10,000 - $50,000 |
| **3D Printer (Plastic & Metal)** | Print customized sensor housings | $2,500 - $30,000 |
| **Coordinate Measuring Machine (CMM)** | Validate machine accuracy | $20,000 - $100,000 |

**Budget Option:**

* **DIY 3D printing solutions** ($5,000) can be used initially.

**3. System Integration Plan**

**3.1 Steps to Digitize the Line Boring Machine**

1. **Sensor Installation:**
   * Attach **IMUs, rotary encoders, laser sensors, and force sensors**.
   * Ensure proper **calibration & alignment** to minimize errors.
2. **Data Acquisition Setup:**
   * Connect all sensors to **DAQ & Edge Computing device**.
   * Store & process data using **LabVIEW, MATLAB, or Python**.
3. **Digital Twin Development:**
   * Build 3D CAD model using **Siemens NX or PTC Creo**.
   * Integrate **real-time sensor data** for predictive monitoring.
4. **Performance Monitoring & AI Integration:**
   * Apply **machine learning (ML) models** for **fault detection & optimization**.
   * Conduct **long-term data analysis** to improve machine efficiency.

**4. Expected Outcomes**

1. **Validation of Digital Twin for predictive maintenance and automation control.**
2. **Enhanced system efficiency by integrating sensor-driven automation into programmable operations.**
3. **Development of a scalable model for other semi-robotic machining processes.**
4. **Evaluation of cost vs. accuracy trade-offs between premium & budget hardware.**
5. **Validation of Digital Twin for predictive maintenance.**
6. **Enhanced system efficiency with real-time motion tracking.**
7. **Development of a scalable model for other machining processes.**
8. **Evaluation of cost vs. accuracy trade-offs between premium & budget hardware.**

**5. Conclusion**

The successful digitization of a **semi-robotic line boring machine** through sensor integration and Digital Twin technology provides a foundation for **real-time monitoring, accuracy enhancement, and predictive maintenance**. By implementing **IMUs, rotary encoders, force sensors, and AI-driven data processing**, this approach enables improved **system efficiency, precision, and automation**. The use of **DAQ systems and Edge Computing** ensures that **sensor data is collected, analyzed, and used for adaptive control** in machining operations.

This test case highlights the viability of integrating **Digital Twin technology** into traditional machining processes, paving the way for **advanced system optimization and process automation**. Future research should focus on **further refining machine learning algorithms** for **predictive maintenance** and exploring **cost-effective alternatives for broader industrial adoption**.

**This test case** establishes a **baseline for digitizing a semi-robotic line boring machine** and evaluating its motion in **3D space** using sensors and Digital Twin technology. Evaluating its motion in **3D space** using sensors and Digital Twin technology.

Evaluate its motion in **3D space** using sensors and Digital Twin technology.

**Appendix I**

**Data Acquisition & Edge Computing Integration**

**1 Data Acquisition (DAQ) System**

* The DAQ system collects signals from all sensors, converts analog signals into digital format, and transmits data for processing.
* **Components:** ADC, signal conditioning module, data logger, communication interface (USB, Ethernet, or wireless).
* **Example DAQ Systems:** National Instruments USB-6361, Advantech DAQ-2010, Raspberry Pi DAQ with ADS1115.

**2 Edge Computing for Real-Time Processing**

* Edge computing processes data locally to reduce latency and enable real-time feedback.
* **Benefits:** Supports AI/ML models for predictive maintenance, reduces cloud dependency, enhances system automation.
* **Example Edge Computing Devices:** Siemens IPC427E, NVIDIA Jetson Xavier NX, Raspberry Pi 4 with Coral TPU.

**Appendix II**

**Data Acquisition (DAQ) & Edge Computing Integration**

To properly digitize your **line boring and bore welding machine**, the **DAQ (Data Acquisition System) and Edge Computing Device** play a crucial role in **real-time data collection, processing, and feedback control**. Integration procedure:

**1. Data Acquisition System (DAQ)**

**Function:** The DAQ collects signals from **all installed sensors** (motion, force, vibration, temperature, spindle speed, etc.), converts them into a **digital format**, and transmits data for real-time analysis.

**1.1Components in the DAQ System:**

* **Analog-to-Digital Converter (ADC):** Converts analog sensor signals into digital data.
* **Signal Conditioning Module:** Amplifies, filters, and prepares signals before processing.
* **Data Logger:** Stores sensor readings for long-term analysis.
* **Communication Interface:** USB, Ethernet, or wireless transmission to Edge Computing Device.

**Example DAQ Systems:**

| **DAQ Type** | **Purpose** | **Example Models** | **Cost Estimate** |
| --- | --- | --- | --- |
| **National Instruments USB-6361** | High-speed multi-sensor data acquisition | NI USB-6361, Advantech DAQ-2010 | $2,500 - $15,000 |
| **Arduino-based DAQ** | Low-cost DIY sensor data collection | Arduino Mega + ADS1115 ADC | $300 - $500 |
| **Raspberry Pi DAQ System** | Compact edge processing DAQ | Raspberry Pi + DAQ HAT | $500 - $1,000 |

**1.2 Edge Computing Device**

**Function:** The **Edge Computing device** processes real-time data **locally**, reducing the need for constant cloud connectivity and enabling **immediate feedback adjustments**.

**1.3 Why Use Edge Computing?**

* **Reduces Latency:** Immediate analysis without waiting for cloud processing.
* **Supports AI/ML Models:** Can implement **real-time predictive maintenance**.
* **Enhances System Automation:** Feeds processed data into **semi-robotic control loops** for **adaptive adjustments**.

**Example Edge Computing Devices:**

| **Device Type** | **Purpose** | **Example Models** | **Cost Estimate** |
| --- | --- | --- | --- |
| **Industrial Edge PC** | High-speed processing for real-time monitoring | Siemens IPC427E, Dell Edge Gateway | $2,500 - $10,000 |
| **NVIDIA Jetson** | AI-powered processing for predictive maintenance | NVIDIA Jetson Xavier NX | $1,000 - $3,500 |
| **Raspberry Pi Edge AI** | Low-cost AI-enabled edge processing | Raspberry Pi 4 + Coral TPU | $500 - $1,000 |

**2.0 How DAQ & Edge Computing Work Together**

1. **Sensors Capture Data** → IMUs, encoders, and force sensors send signals to the DAQ.
2. **DAQ Digitizes & Transmits Data** → Data is sent to the **Edge Computing Device**.
3. **Edge Computing Analyzes Data** → AI/ML models detect **anomalies, tool wear, and misalignment**.
4. **Feedback Loop** → Results are sent back to the **machine control system** for **real-time adjustment**.

**Practical Implementation in Your Line Boring Machine**

1. **Mount the DAQ inside the control cabinet** of your machine.
2. **Connect all sensors** (IMU, rotary encoders, force gauges, temperature sensors).
3. **Process data on an Edge PC or Raspberry Pi** and display results on an HMI (Human-Machine Interface).
4. **Integrate AI-powered feedback control** to **optimize cutting & welding paths**