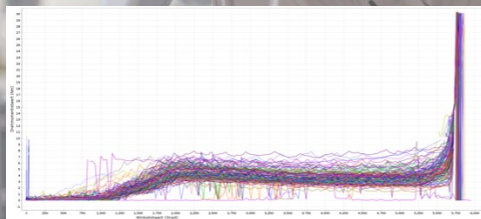




University of Stuttgart
Institute of Industrial Automation
and Software Engineering



Investigation of Textual Representation Methods for Enhanced LLM Interpretation of Time Series Data

Presenter: Sijia Chen

Supervisor: Yuchen Xia M. Sc.

Examiner: Prof. Dr. Ing. Michael Weyrich

Research Question:

How to use LLM to analyze the time series data?



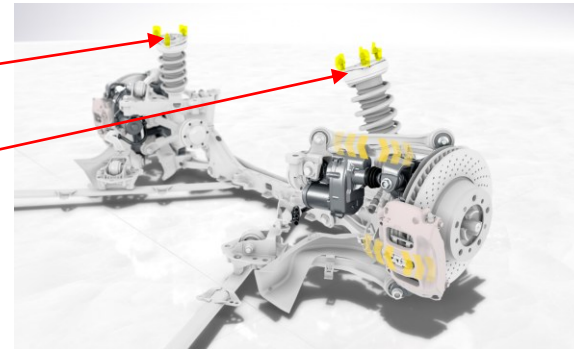
Introduction

Application use case: bolt tightening

Introducing the application scenario

Quality-critical process: bolt tightening

200 vehicles
x 500 points =
100 000 bolts

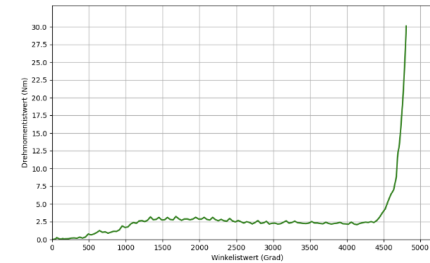


bolts connect the wheel axle to the car body



tightening gun

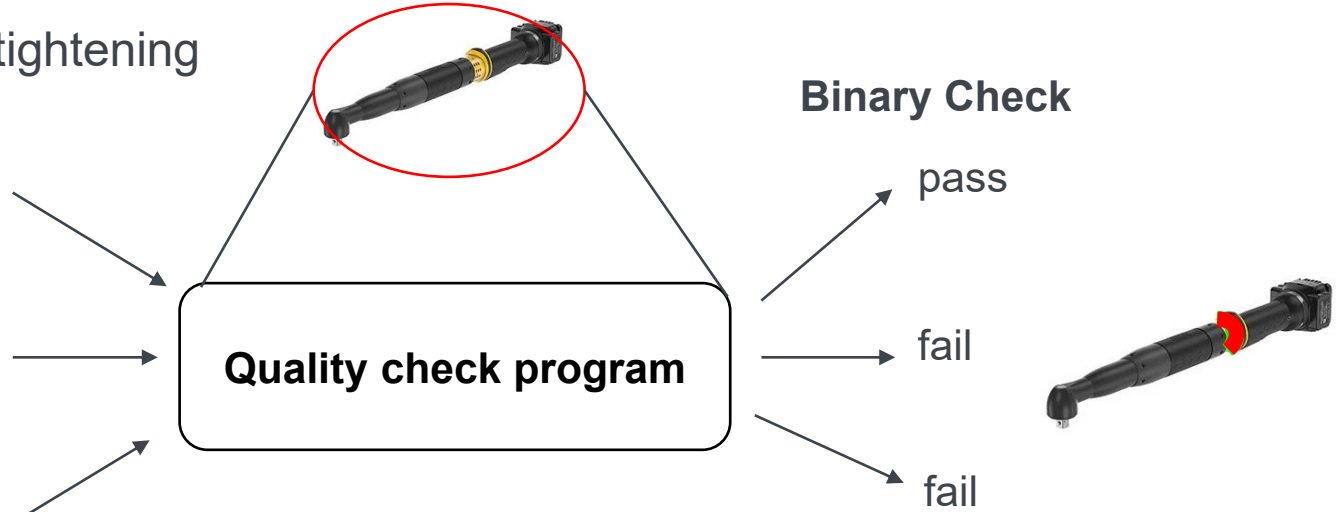
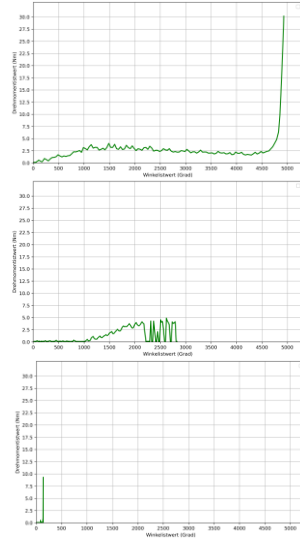
record



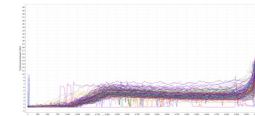
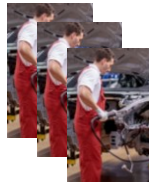
Tightening curve

The Use Case

Quality Check: Bolt tightening



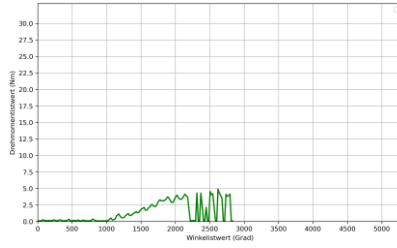
More than **5000** failures



“Fail” → Re-tighten 3 times → Need engineers manual inspection

Automated Quality Diagnosis System to assist the engineers to classify the quality issues

How expert perform the diagnosis



Domain expert

↓ reasoning

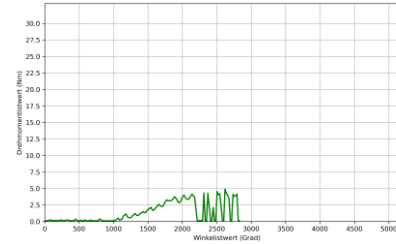
“Slipping”



Potential root cause:

1. a problem with the nut
2. wear on the tightening gun head

Can this process be automated?



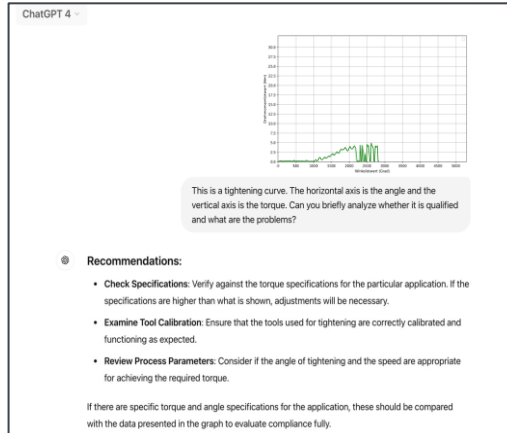
Domain expert LLM

↓ reasoning

“Slipping”

Can LLM perform this task?

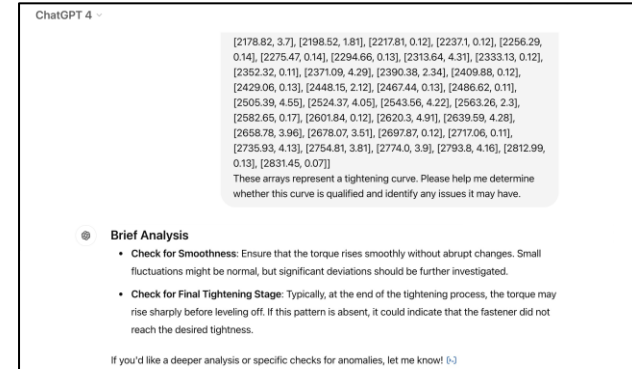
No



- General advice
- **Lacks** the domain-specific **expert knowledge** when dealing with this specialized task

Reserach Question 1

How can LLM have the **expert knowledge**?



Not suitable to process time series data, beacuse the **numbers lack conceptual meaning** and are too complex.

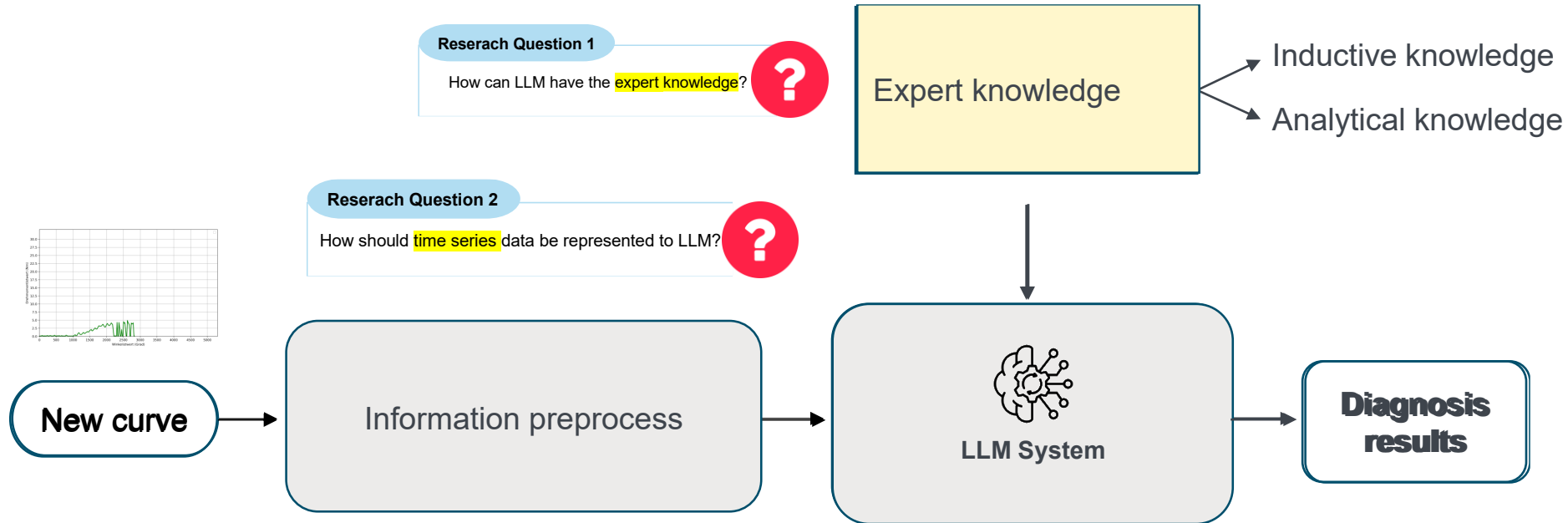
Reserach Question 2

How should **time series** data be represented so that a large language model can understand it and perform more effective reasoning?

Conceptual Design

- Information processing pipeline for **time series data**
- **Expert Knowledge**

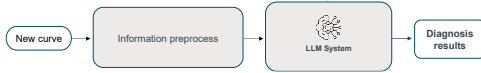
Conceptual system design



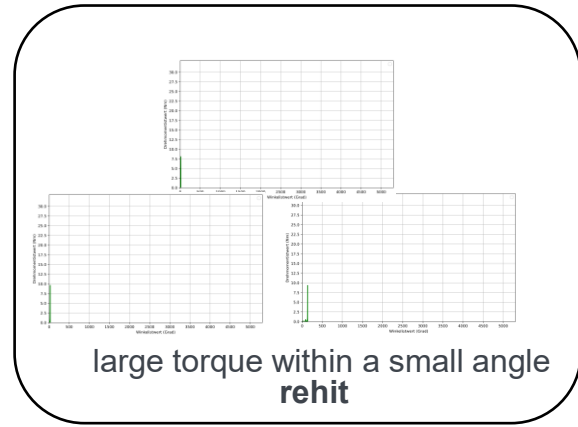
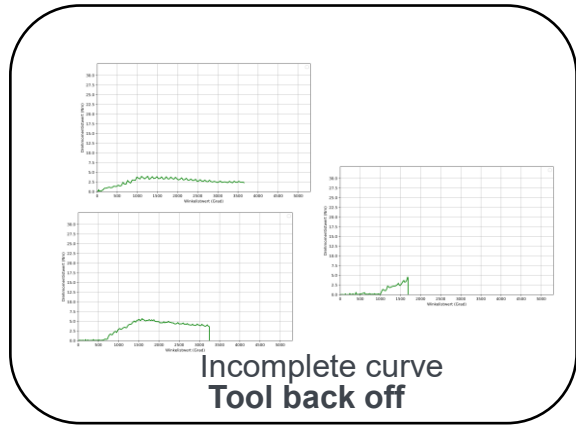
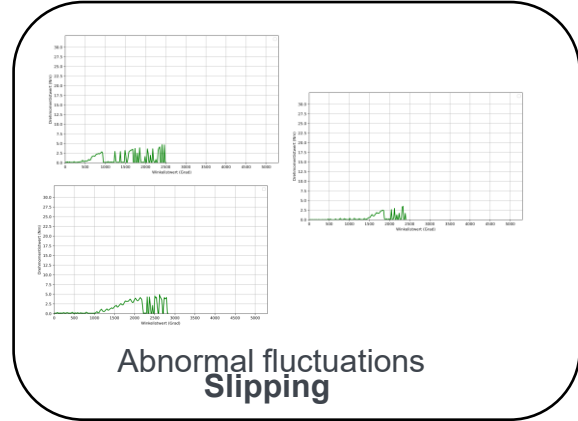
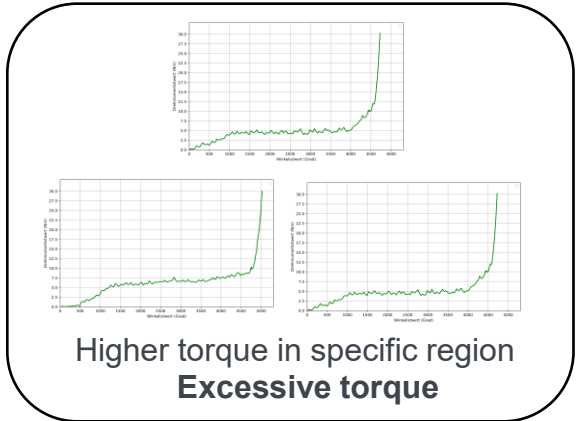
Expert Knowledge

- Inductive knowledge
- Analytical knowledge

Expert knowledge: useful for reasoning and decision-making

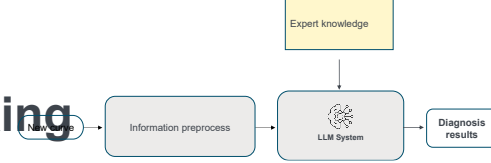


Inductive knowledge: types of the curve

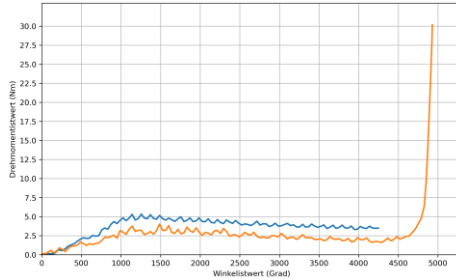


Expert knowledge: useful for reasoning and decision-making

Analytical knowledge: features of the curve

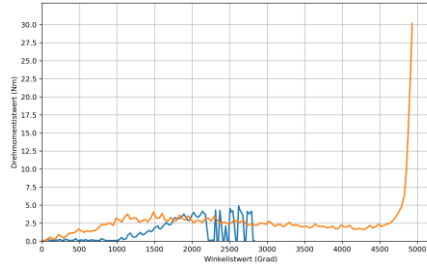


Time feature



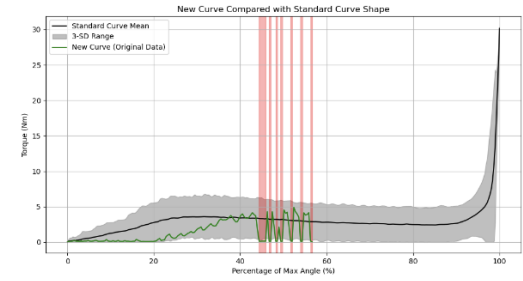
- Maximum **Angle: 1256.98°**
- Corresponding **torque: 5.33Nm**

Frequency feature



- Center **Frequency: 0.0324 Hz**
- High **Frequency Energy Ratio: 5.0911%**

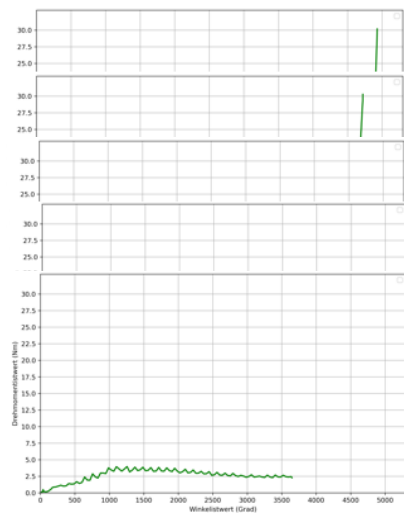
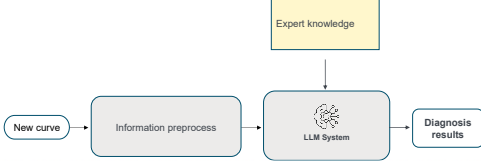
Shape feature



- Calculate mean and 3 standard **deviations** of qualified curves
- “**Out of bounds** from 44.36% to 45.89% with torque lower than standard...

Expert knowledge

Specifying expert knowledge into text



Tool back off

Conceptual system design

Research Question 1

How can LLM have the **expert knowledge**?



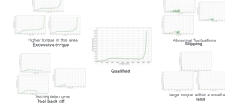
Research Question 2

How should **time series** data be represented to LLM?

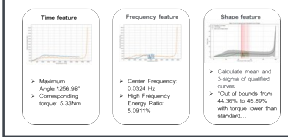


Expert knowledge

Inductive



Analytical

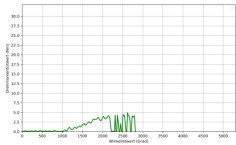


LLM System

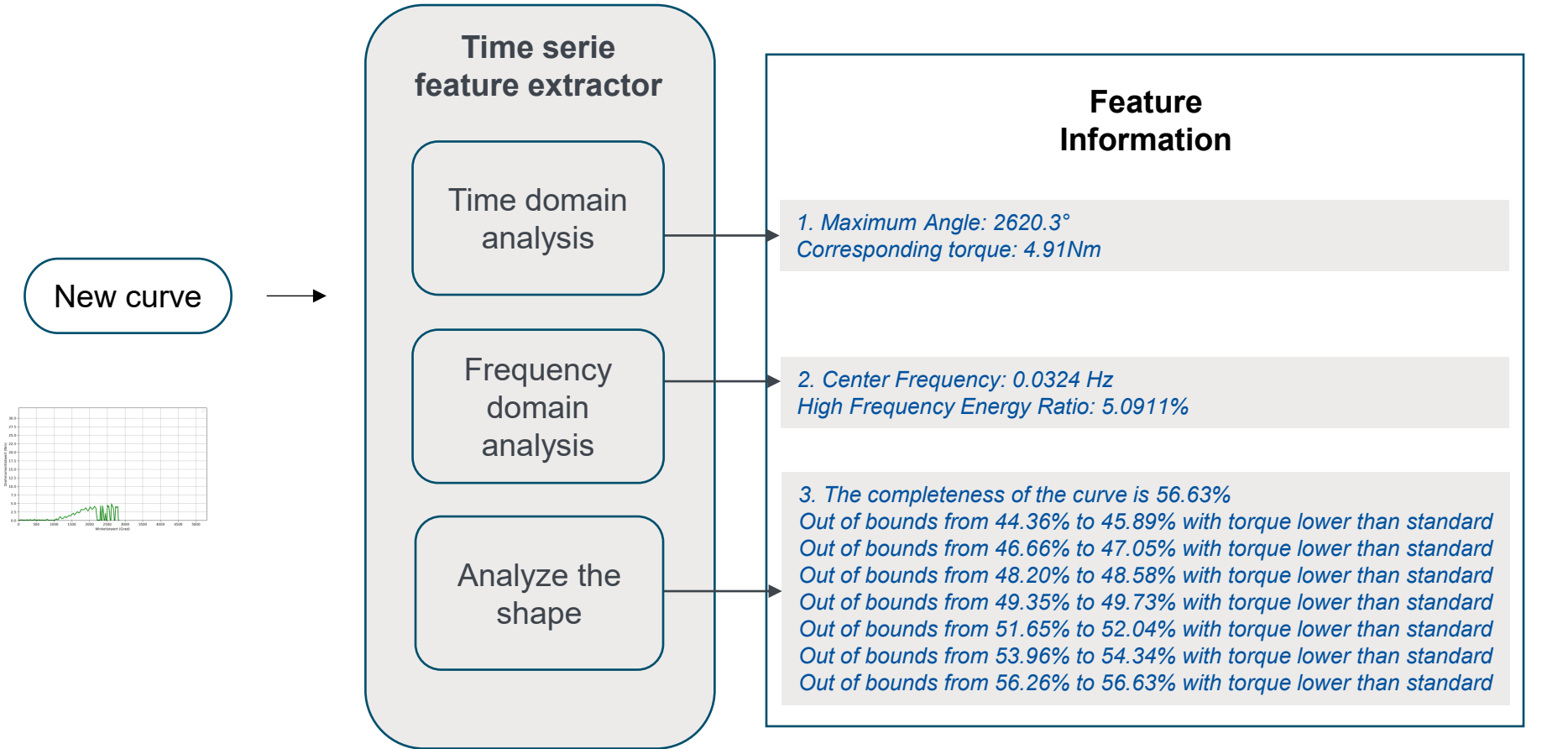
New curve

Information preprocessing

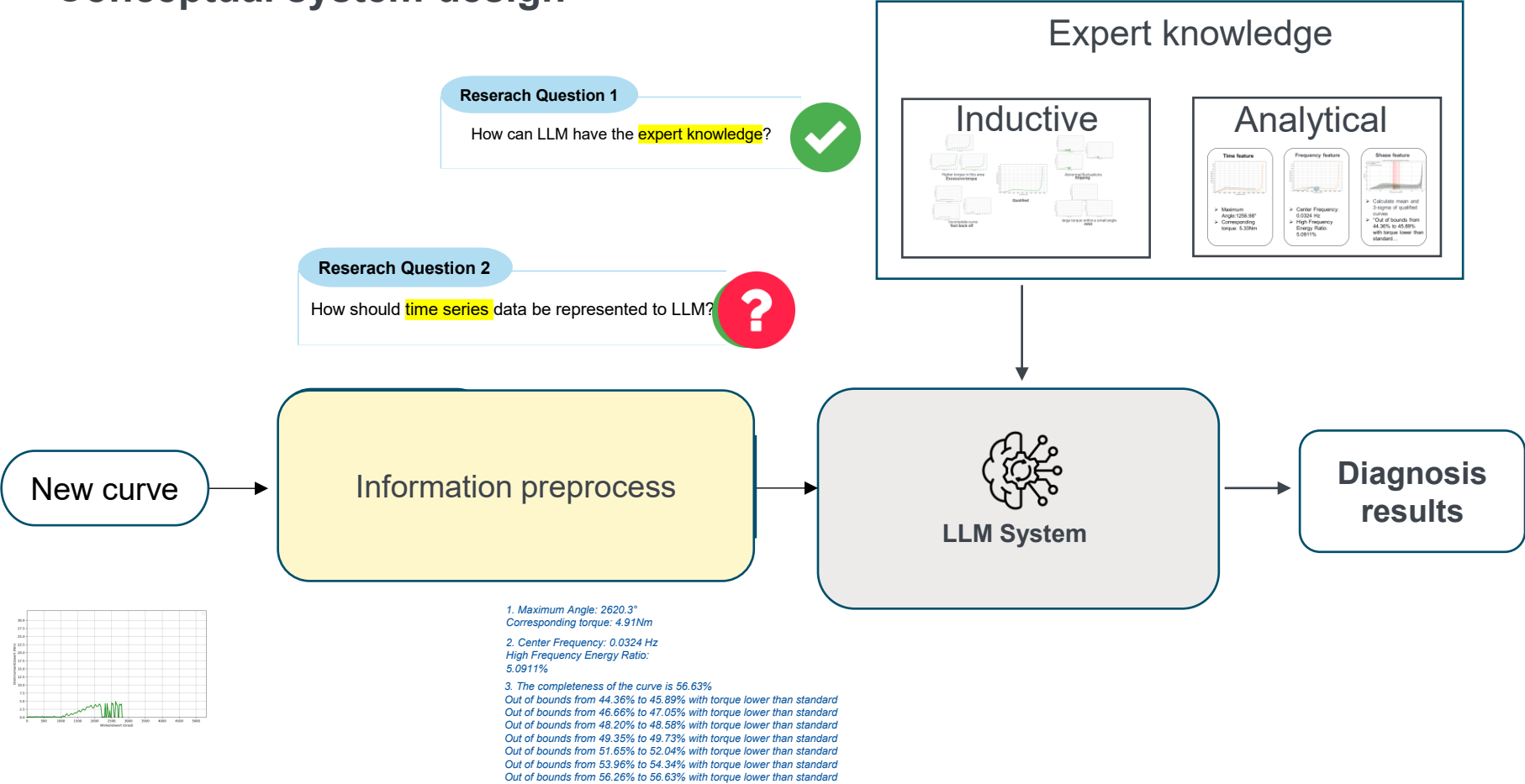
Diagnosis results



Information preprocessing



Conceptual system design



Conceptual system design

Research Question 1

How can LLM have the expert knowledge?



Research Question 2

How should time series data be represented to LLM?

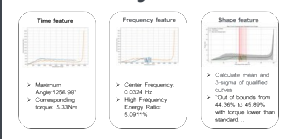


Expert knowledge

Inductive



Analytical



New curve

Time serie
feature
extractor

Textual
information

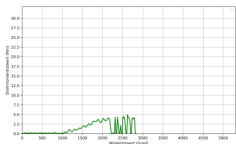


prompt



LLM

Diagnosis
results



1. Maximum Angle: 2620.3°
Corresponding torque: 4.91Nm
2. Center Frequency: 0.0324 Hz
High Frequency Energy Ratio:
5.0911%
3. The completeness of the curve is 56.63%
Out of bounds from 44.36% to 45.89% with torque lower than standard
Out of bounds from 46.66% to 47.05% with torque lower than standard
Out of bounds from 48.20% to 48.58% with torque lower than standard
Out of bounds from 49.35% to 49.73% with torque lower than standard
Out of bounds from 51.65% to 52.04% with torque lower than standard
Out of bounds from 53.96% to 54.34% with torque lower than standard
Out of bounds from 56.26% to 56.63% with torque lower than standard

Prompt design

Role and Goal:
You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output.

Context:
Characteristics of different curve types in the expert database

Type1 Standard curve:
1. Time characteristics+++
Angle: 4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0

Type2 Excessive Torque:
1. Time characteristics:
Angle: 4513.24° to 5315.68°
Torque range: more than 30Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0
3. Standard Curve Comparison+++
This type of curve is mostly complete, with its most notable feature being the torque exceeding the standard range, particularly in the mid to late stages of the process.

Type3 Rehit
1. Time characteristics+++
Angle range: 6.51° to 138.50°
Torque range: 7.02 Nm to 12.34 Nm
2. Frequency characteristics:
Center Frequency range: nan
High Frequency Energy Ratio range: 26.4306% to 85.8581%
3. Standard Curve Comparison:
This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning.

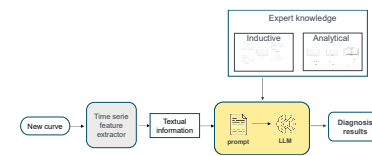
Type4 stripping
1. Time characteristics:
Angle range: 998.69° to 5174.18°
Torque range: 1.62 Nm to 15.05 Nm
2. Frequency characteristics+++
Center Frequency range: 0.0104 Hz to 0.1472 Hz
High Frequency Energy Ratio range: 0 to 41.3477%
3. Standard Curve Comparison:
This type of curve is typically incomplete, with frequent and consistent deviations below the standard torque range throughout its latter half.

Type5 Tool backoff
1. Time characteristics:
Angle range: 711.93° to 4451.52°
Torque range: 0.0 Nm to 11.07 Nm
2. Frequency characteristics:
Center Frequency (Hz) range: 0.0051 Hz to 0.0063 Hz
High Frequency Energy Ratio (%) range: 0.0000% to 0.9334%
3. Standard Curve Comparison+++
This type of curve is typically incomplete, but within the standard range.

Instructions:
Compare the characteristics of the input curve with those of the five curve types from the expert database, each defined by three key features. Evaluate how closely the input curve's features align with each curve type, giving extra weight to features marked with a "+", as they are crucial for distinguishing between different types. First, provide a concise reason for the similarity ranking, then rank these types accordingly, from most to least similar.
You should follow the following output pattern to generate your response in JSON format:
Output template:
{
 "similarity_rank": [{"reason": "a_concise_explanation", "1.": "a_type"},
 {"reason": "a_concise_explanation", "2.": "a_type"},
 {"reason": "a_concise_explanation", "3.": "a_type"},
 {"reason": "a_concise_explanation", "4.": "a_type"},
 {"reason": "a_concise_explanation", "5.": "a_type"}]
}

Input:
{
 1. Torque: 4.25
 Angle: 2082.79
 2. Center Frequency: 0.0157 Hz
 High Frequency Energy Ratio: 0.2805%
 3. The completeness of the curve is 58.18%
 Out of bounds from 4.80% to 5.18% with torque higher than standard
}

Output:



Agent Task Description

“You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output. ”

Prompt design

Role and Goal:
You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output.

```
Context:
Characteristics of different curve types in the expert database

Type1 Standard curve:
1. Time characteristics+++
Angle:4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0

Type2 Excessive Torque:
1. Time characteristics:
Angle: 4513.24° to 5315.68°
Torque range: more than 30Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0
3. Standard Curve Comparison+++
This type of curve is mostly complete, with its most notable feature being the torque exceeding the standard range, particularly in the mid to late stages of the process.

Type3 Rehit
1. Time characteristics+++
Angle range: 6.51° to 138.50°
Torque range: 7.02 Nm to 12.34 Nm
2. Frequency characteristics:
Center Frequency range: nan
High Frequency Energy Ratio range: 26.4306% to 85.0581%
3. Standard Curve Comparison:
This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning.

Type4 stripping
1. Time characteristics:
Angle range: 998.69° to 5174.10°
Torque range: 1.62 Nm to 15.05 Nm
2. Frequency characteristics+++
Center Frequency range: 0.0104 Hz to 0.1472 Hz
High Frequency Energy Ratio range: 0 to 41.3477%
3. Standard Curve Comparison:
This type of curve is typically incomplete, with frequent and consistent deviations below the standard torque range throughout its latter half.

Type5 Tool backoff
1. Time characteristics:
Angle range: 711.93° to 4451.52°
Torque range: 0.0 Nm to 11.07 Nm
2. Frequency characteristics:
Center Frequency (Hz) range: 0.0051 Hz to 0.0063 Hz
High Frequency Energy Ratio (%) range: 0.0000% to 0.9334%
3. Standard Curve Comparison+++
This type of curve is typically incomplete, but within the standard range.
```

Instructions:
Compare the characteristics of the input curve with those of the five curve types from the expert database, each defined by three key features. Evaluate how closely the input curve's features align with each curve type, giving extra weight to features marked with a "+", as they are crucial for distinguishing between different types. First, provide a concise reason for the similarity ranking, then rank these types accordingly, from most to least similar.
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 {"reason": "a_concise_explanation", "3.": "a_type"},
 {"reason": "a_concise_explanation", "4.": "a_type"},
 {"reason": "a_concise_explanation", "5.": "a_type"}]
}

Input:
{
 1. Torque: 4.25
 Angle: 2082.79
 2. Center Frequency: 0.0157 Hz
 High Frequency Energy Ratio: 0.2805%
 3. The completeness of the curve is 58.18%
 Out of bounds from 4.80% to 5.18% with torque higher than standard)
}

Output:

Context (Expert knowledge)

“ Features of different curve types in the expert knowledge base.

...

Type3 Rehit

1. Time characteristics+++:

Angle range: 6.51° to 138.50°

Torque range: 7.02 Nm to 12.34 Nm

2. Frequency characteristics:

Center Frequency range: nan

High Frequency Energy Ratio range: 26.4306% to 85.0581%

3. Standard Curve Comparison:

This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning... ”

Prompt design

Role and Goal:
You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output.

Context:
Characteristics of different curve types in the expert database

Type1 Standard curve:
1. Time characteristics++:
Angle: 4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0

Type2 Excessive Torque:
1. Time characteristics:
Angle: 4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0
3. Standard Curve Comparison++:
This type of curve is mostly complete, with its most notable feature being the torque exceeding the standard range, particularly in the mid to late stages of the process.

Type3 Rehit
1. Time characteristics++:
Angle range: 6.51° to 138.50°
Torque range: 7.02 Nm to 12.34 Nm
2. Frequency characteristics:
Center Frequency range: nan
High Frequency Energy Ratio range: 26.4306% to 85.8581%
3. Standard Curve Comparison:
This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning.

Type4 stripping
1. Time characteristics:
Angle range: 998.69° to 5174.18°
Torque range: 1.62 Nm to 15.05 Nm
2. Frequency characteristics++:
Center Frequency range: 0.0104 Hz to 0.1472 Hz
High Frequency Energy Ratio range: 0 to 41.3477%
3. Standard Curve Comparison:
This type of curve is typically incomplete, with frequent and consistent deviations below the standard torque range throughout its latter half.

Type5 Tool backoff
1. Time characteristics:
Angle range: 711.93° to 4451.52°
Torque range: 0.0 Nm to 11.07 Nm
2. Frequency characteristics:
Center Frequency (Hz) range: 0.0051 Hz to 0.0063 Hz
High Frequency Energy Ratio (%) range: 0.0000% to 0.9334%
3. Standard Curve Comparison++:
This type of curve is typically incomplete, but within the standard range.

Instructions:
Compare the characteristics of the input curve with those of the five curve types from the expert database, each defined by three key features. Evaluate how closely the input curve's features align with each curve type, giving extra weight to features marked with a '+', as they are crucial for distinguishing between different types. First, provide a concise reason for the similarity ranking, then rank these types accordingly, from most to least similar.

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 {"reason": "a_concise_explanation", "3.": "a_type"},
 {"reason": "a_concise_explanation", "4.": "a_type"},
 {"reason": "a_concise_explanation", "5.": "a_type"}]
}

Input:
{
 1. Torque: 4.25
 Angle: 2082.79
 2. Center Frequency: 0.0157 Hz
 High Frequency Energy Ratio: 0.2805%
 3. The completeness of the curve is 58.18%
 Out of bounds from 4.80% to 5.18% with torque higher than standard
}

Output:

Instructions

- “ Compare the features of the input curve with predefined five types in the expert knowledge, each defined by three key features.
- Evaluate how closely the input curve's features align with each curve type, giving extra weight to features marked with a '+', as they are crucial for distinguishing between different types.
- First, provide a concise reason for the similarity ranking, then rank these types accordingly, from most to least similar.
- You should follow the following output pattern to generate your diagnosis in JSON format:
Output template:

```
{  
  "similarity_rank": [{"reason":  
    "a_concise_explanation", "1.": "a_type"},  
    {"reason": "a_concise_explanation", "2.":  
    "a_type"},  
    {"reason": "a_concise_explanation", "3.":  
    "a_type"},  
    {"reason": "a_concise_explanation", "4.":  
    "a_type"},  
    {"reason": "a_concise_explanation", "5.":  
    "a_type"}]  
}
```

Prompt design

Role and Goal:
You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output.

Context:
Characteristics of different curve types in the expert database

Type1 Standard curve:
1. Time characteristics+++
Angle:4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0

Type2 Excessive Torque:
1. Time characteristics:
Angle: 4513.24° to 5315.68°
Torque range: more than 30Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0
3. Standard Curve Comparison+++
This type of curve is mostly complete, with its most notable feature being the torque exceeding the standard range, particularly in the mid to late stages of the process.

Type3 Rehit
1. Time characteristics+++
Angle range: 6.51° to 138.50°
Torque range: 7.02 Nm to 12.34 Nm
2. Frequency characteristics:
Center Frequency range: nan
High Frequency Energy Ratio range: 26.4306% to 85.8581%
3. Standard Curve Comparison:
This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning.

Type4 stripping
1. Time characteristics:
Angle range: 998.69° to 5174.18°
Torque range: 1.62 Nm to 15.05 Nm
2. Frequency characteristics+++
Center Frequency range: 0.0104 Hz to 0.1472 Hz
High Frequency Energy Ratio range: 0 to 41.3477%
3. Standard Curve Comparison:
This type of curve is typically incomplete, with frequent and consistent deviations below the standard torque range throughout its latter half.

Type5 Tool backoff
1. Time characteristics:
Angle range: 711.93° to 4451.52°
Torque range: 0.0 Nm to 11.07 Nm
2. Frequency characteristics:
Center Frequency (Hz) range: 0.0051 Hz to 0.0063 Hz
High Frequency Energy Ratio (%) range: 0.0000% to 8.9334%
3. Standard Curve Comparison+++
This type of curve is typically incomplete, but within the standard range.

Instructions:
Compare the characteristics of the input curve with those of the five curve types from the expert database, each defined by three key features. Evaluate how closely the input curve's features align with each curve type, giving extra weight to features marked with a "+", as they are crucial for distinguishing between different types. First, provide a concise reason for the similarity ranking, then rank these types accordingly, from most to least similar.
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 {"reason": "a_concise_explanation", "3.": "a_type"},
 {"reason": "a_concise_explanation", "4.": "a_type"},
 {"reason": "a_concise_explanation", "5.": "a_type"}]
}

Input:
{
 1. Torque: 4.25
 Angle: 2082.79
 2. Center Frequency: 0.0157 Hz
 High Frequency Energy Ratio: 0.2805%
 3. The completeness of the curve is 58.18%
 Out of bounds from 4.80% to 5.18% with torque higher than standard
}

Output:

Input

*“1. Angle: 2620.3°
Torque: 4.91 Nm*

*2. Center Frequency: 0.0324 Hz
High Frequency Energy Ratio: 5.0911%*

*3. The completeness of the curve is 56.63%
Out of bounds from 44.36% to 45.89% with
torque lower than standard
Out of bounds from 46.66% to 47.05% with
torque lower than standard
Out of bounds from 48.20% to 48.58% with
torque lower than standard...”*

Output

Role and Goal:
You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output.

Context:
Characteristics of different curve types in the expert database

Type1 Standard curve:
1. Time characteristics+++
Angle: 4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0

Type2 Excessive Torque:
1. Time characteristics:
Angle: 4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0
3. Standard Curve Comparison+++
This type of curve is mostly complete, with its most notable feature being the torque exceeding the standard range, particularly in the mid to late stages of the process.

Type3 Rehit
1. Time characteristics+++
Angle range: 6.51° to 138.58°
Torque range: 7.02 Nm to 12.34 Nm
2. Frequency characteristics:
Center Frequency range: nan
High Frequency Energy Ratio range: 26.4306% to 85.8581%
3. Standard Curve Comparison:
This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning.

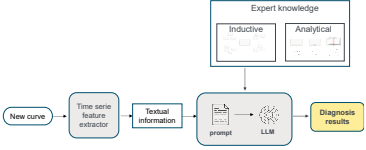
Type4 stripping
1. Time characteristics:
Angle range: 998.69° to 5174.18°
Torque range: 1.62 Nm to 15.05 Nm
2. Frequency characteristics+++
Center Frequency range: 0.0104 Hz to 0.1472 Hz
High Frequency Energy Ratio range: 0 to 41.3477%
3. Standard Curve Comparison:
This type of curve is typically incomplete, with frequent and consistent deviations below the standard torque range throughout its latter half.

Type5 Tool backoff
1. Time characteristics:
Angle range: 711.93° to 4451.52°
Torque range: 0.0 Nm to 11.07 Nm
2. Frequency characteristics:
Center Frequency (Hz) range: 0.0051 Hz to 0.0063 Hz
High Frequency Energy Ratio (%) range: 0.0000% to 8.9334%
3. Standard Curve Comparison+++
This type of curve is typically incomplete, but within the standard range.

Instructions:
Compare the characteristics of the input curve with those of the five curve types from the expert database, each defined by three key features. Evaluate how closely the input curve's features align with each curve type, giving extra weight to features marked with a "+", as they are crucial for distinguishing between different types. First, provide a concise reason for the similarity ranking, then rank these types accordingly, from most to least similar.
You should follow the following output pattern to generate your response in JSON format:
Output template:
{
 "similarity rank": [{"reason": "a_concise_explanation", "1.": "a_type"},
 {"reason": "a_concise_explanation", "2.": "a_type"},
 {"reason": "a_concise_explanation", "3.": "a_type"},
 {"reason": "a_concise_explanation", "4.": "a_type"},
 {"reason": "a_concise_explanation", "5.": "a_type"}]
}

Input:
{
 1. Torque: 4.25
 Angle: 2082.79
 2. Center Frequency: 0.0157 Hz
 High Frequency Energy Ratio: 0.2805%
 3. The completeness of the curve is 58.18%
 Out of bounds from 4.80% to 5.18% with torque higher than standard
}

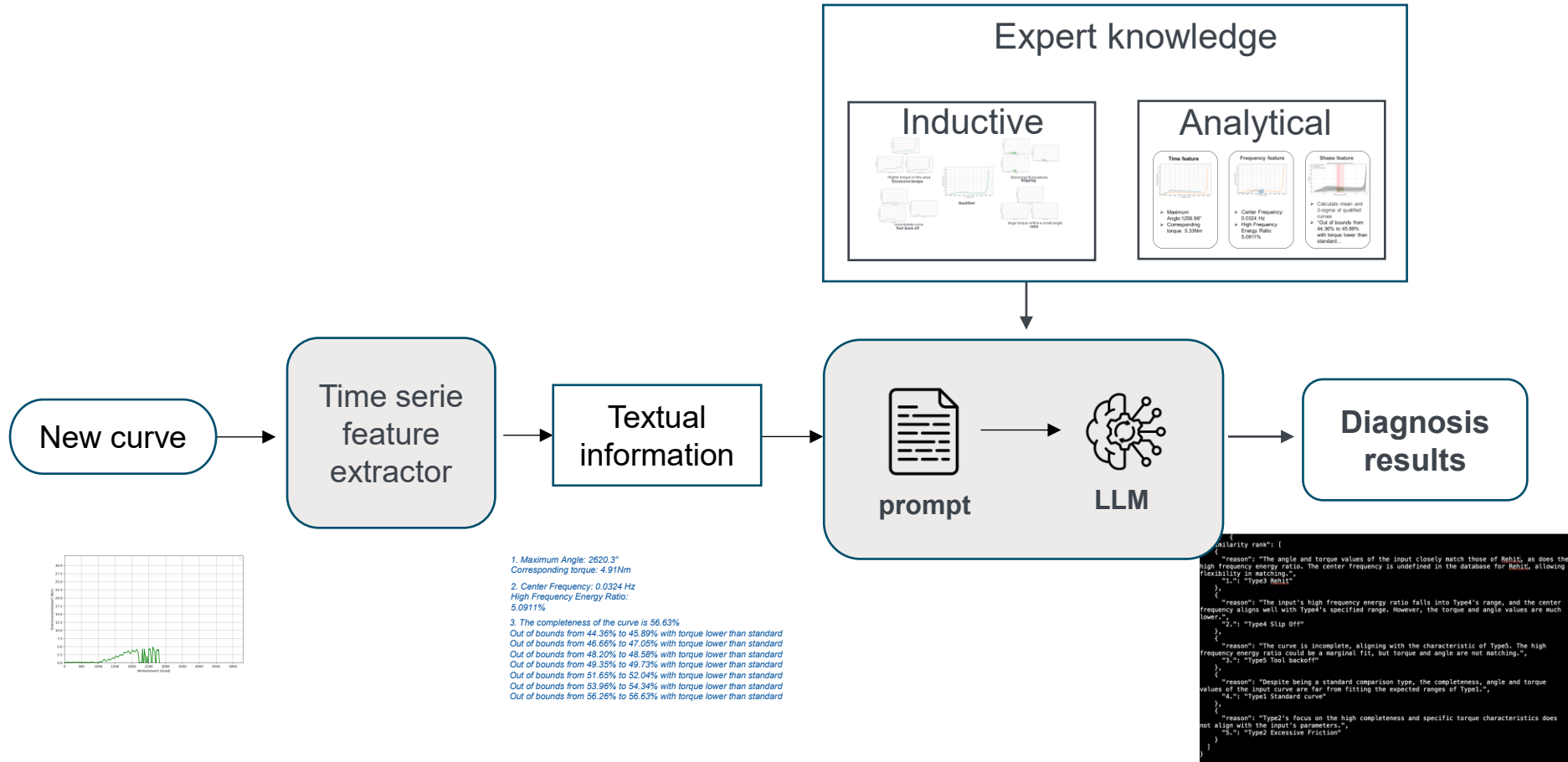
Output:



```
GPT-4: {  
  "similarity rank": [  
    {  
      "reason": "Type4 is the most similar as it covers a similar angle range and exhibits torque deviations below the standard, which aligns closely with the input's multiple readings. The frequency characteristics are also within a comparable range.",  
      "1.": "Type4 Slip Off"  
    },  
    {  
      "reason": "Type5 follows due to its similar angle range and the incomplete nature of curves. Although its torque range is higher than the input's, the frequency characteristics and the frequent deviations make it a reasonable match.",  
      "2.": "Type5 Tool backoff"  
    },  
    {  
      "reason": "Type3, despite having a much narrower angle and torque range, aligns with the input's pattern of having high frequency energy ratios and significant variations in torque, somewhat matching the input's pattern of frequent torque deviations.",  
      "3.": "Type3 Rehit"  
    },  
    {  
      "reason": "Type1 and Type2, with their high torque values and larger angle ranges, align well with the input's characteristics. Between them, Type1 is less similar due to its incomplete curve nature and lack of high frequency energy, contrasting more with the input's completeness and higher frequency values.",  
      "4.": "Type1 Standard curve"  
    },  
    {  
      "reason": "Type2, while also having high torque and large angles, is ranked slightly less similar than Type1 because it notes torque exceedances, albeit in the opposite direction of the input's lower-than-standard readings, offering a marginally closer behavioral comparison.",  
      "5.": "Type2 Excessive Friction"  
    }  
  ]  
}
```

Realization

Designing information processing pipeline: LLM System for reasoning



Experiment Evaluation

Evaluation with GPT4

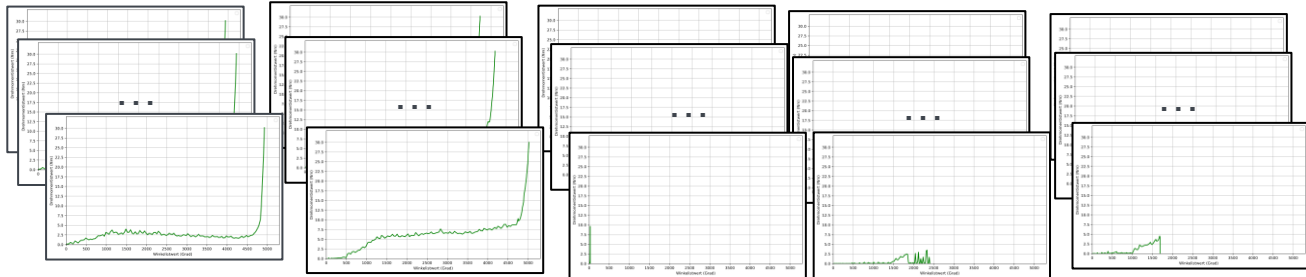
Results

Evaluation metrics

Correctness Rate: binary decision

Reason Plausibility: rated by humans from 1 to 5

50 samples



	Pass	Failure 1: Excessive torque	Failure 2: Rehit	Failure 3: Slipping	Failure 4: Tool backoff	Total
Correctness rate	90.00%	100.00%	100.00%	100.00%	40.00%	86.00%
Reason Plausibility	5	4.8	5	5	4.1	4.78

Reason for incorrect result was:
The expert knowledge is not clearly expressed with
language in prompt.

After interview with expert

To express the expert knowledge more clearly with language

Role and Goal:

You are a tightening expert. Your task is to compare the characteristics of the input tightening curve with those of various curve types in an expert database to identify the most similar type, and then generate the output.

Context:

Features of different curve types in the expert database

Type1 Standard curve

Definition: The correct torque-angle relationship, where the fastener reaches the target torque within the specified angle range, ensuring proper and secure tightening.

Typical characteristics

1. Time characteristics+++

Angle: 14513.24° to 5315.68°

Torque range: more than 30 Nm

2. Frequency characteristics:

Center Frequency range: 0.0079 Hz to 0.0102 Hz

High Frequency Energy Ratio range: 0

3. Standard Curve Comparison++

This type of curve is complete, and all torque staying within the standard range.

Type2 Excessive Torque

Definition: This type of curve may occur due to excessive friction between the fastener and the material being fastened, leading to an increase in the required torque for a given angle.

Typical characteristics

1. Time characteristics:

Angle range: 2216.89° to 5299.82°

Torque range: 2.41 Nm to 30.27 Nm

2. Frequency characteristics:

Center Frequency (Hz) range: 0.0033 Hz to 0.0157 Hz

High Frequency Energy Ratio (%) range: 0.0000% to 0.3001%

3. Standard Curve Comparison+++

This type of curve is particularly notable for the torque exceeding the standard range, especially in the mid to late stages of the process.

Type3 Rehit

Definition: The process of applying additional torque to a fastener that has already been tightened, typically causing a rapid increase in torque over a short angle range.

Typical characteristics

1. Time characteristics+++

Angle range: 6.51° to 138.50°

Torque range: 7.02 Nm to 12.34 Nm

2. Frequency characteristics:

Center Frequency range: nan

High Frequency Energy Ratio range: 26.4306% to 85.0581%

3. Standard Curve Comparison:

This type of curve exceeds the standard range early on, with torque higher than the standard from the beginning.

Type4 Stripping

Definition: During the tightening process, the fastener loses grip with the threads, causing the torque to repeatedly drop and rise as the tool attempts to continue tightening without success.

Typical characteristics

1. Time characteristics:

Angle range: 998.69° to 5174.18°

Torque range: 1.62 Nm to 15.05 Nm

2. Frequency characteristics+++

Center Frequency range: 0.0104 Hz to 0.1472 Hz

High Frequency Energy Ratio range: 0 to 41.3477%

3. Standard Curve Comparison:

This type of curve is often incomplete, with typically short and frequent deviations below the standard range, which tend to appear more often towards the latter part of the curve.

Type5 Tool backoff:

Definition: Occurs when the torque tool momentarily stops applying torque due to a sudden release or disengagement, causing incomplete tightening.

Typical characteristics

1. Time characteristics:

Angle range: 711.93° to 4249.55°

Torque range: 0.43 Nm to 4.27 Nm

2. Frequency characteristics:

Center Frequency (Hz) range: 0.0043 Hz to 0.0863 Hz

High Frequency Energy Ratio (%) range: 0.0000% to 8.9334%

3. Standard Curve Comparison+++

This type of curve is typically incomplete, with most torque staying within the standard range.

Evaluation

Results after Iterative improvement of prompt

	Pass	Failure 1: Excessive torque	Failure 2: Rehit	Failure 3: Slipping	Failure 4: Tool backoff	Total
Correctness rate	100.00% (90.00%)	100.00%	100.00%	100.00%	71.43% (40.00%)	96.00% (86.00%)
Reason Plausibility	5	5 (4.8)	5	5	4.3 (4.1)	4.9 (4.78)

Conclusion: if the expert knowledge is defined clearly in prompt with language, the LLM can have better performance, up to 100% accuracy

Critical conditions:

- Expert knowledge must be accurate
- Language must be accurate

Summary and Outlook

Comparison with other approaches

Related works

How this approach superior to other methods

- Neural network based

[1] Process curve analysis with machine learning on the example of screw fastening and press-in processes

[2] A Comparison of Anomaly Detection Methods for Industrial Screw Tightening

- Decision tree / rule based classification

Advantage:

- Semantic interpretation, transferable knowledge (pretraining knowlegde of LLM)
- LLM system easier to reconfigure with natural language

Type1 Standard curve:
1. Time characteristics+++
Angle:4513.24° to 5315.68°
Torque range: more than 30 Nm
2. Frequency characteristics:
Center Frequency range: 0.0079 Hz to 0.0102 Hz
High Frequency Energy Ratio range: 0

Disadvantage: High hardware requirements / computational complexity

Summary and future work

Summary:

- Integrate expert knowledge with structured feature extraction, allowing the large language model to interpret time series data.
- Realize automated diagnosis, allowing for efficient identification and analysis of tightening issues.

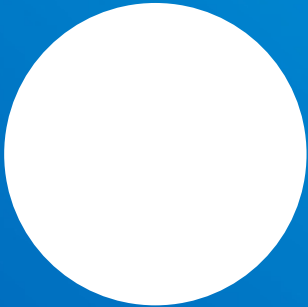
Future work:

- Experimenting with more complex datasets
- Potential for software product to assist the engineer to analyze 5 000 samples per day.



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and Software Engineering

Thank you!



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Quelle

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