



# HUMS2023 Data Challenge Result Submission

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**Institutions:** Cranfield University

**Publishable:** Yes

## 1. Summary of Findings

This report summarizes the findings of the data challenge that The Defence Science and Technology Group (DSTG) prepared for the upcoming HUMS2023 Conference. The challenges involved the earliest convincing detection of the planet gear crack and the best trending capability of the crack progression. After exploring various combinations of relevant signal processing techniques, automated cepstral editing followed by synchronous signal averaging (SSA) is taken into consideration to enhance crack-related signatures in the signal for both challenges. Each channel signal is processed using this procedure. Eight features are then extracted from each processed signal. The feature ranking based on the monotonicity metric is carried out to select the most relevant feature that can be used for early detection and trending. The analysis shows that the kurtosis of the enhanced signal is the most relevant feature. It is found that the kurtosis feature of the enhanced signal calculated from channel 2 could detect the crack at the earliest with the CUSUM method. The earliest detection is found on channel 2 at file number 346. Subsequently, the crack can be detected using the same procedure on channel 1 at file number 421.

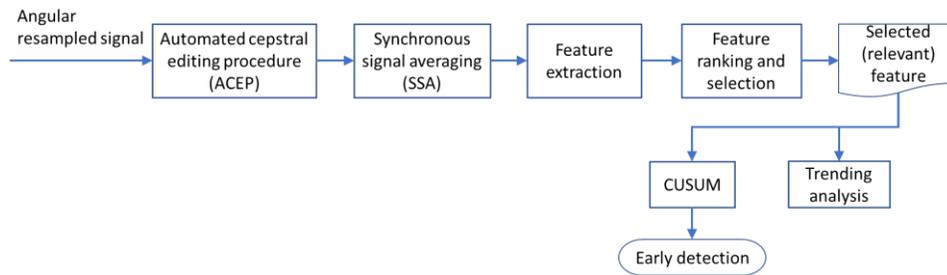
*Table 1 Summary of Analysis Results*

#	Detection & Trending	Data file name/number	Comments
1	Consistent detection on at least one signal channel; i.e. the fault indicators remain consistently above the threshold.	<ul style="list-style-type: none"> <li>File#: 346</li> <li>Filename: 'Day025_Hunting_SSA_20220111_110020.mat'</li> </ul>	<ul style="list-style-type: none"> <li>The change of the fault indicator (Feature 2) is detected by the CUSUM analysis on Channel 2.</li> <li>See Figure 1(b)</li> </ul>
2	Confirmed detection on at least two signal channels; i.e. the fault indicators remain consistently above the threshold.	<ul style="list-style-type: none"> <li>File#432</li> <li>Filename: 'Day026_Hunting_SSA_20220114_111444.mat'</li> </ul>	<ul style="list-style-type: none"> <li>After File#432, Feature 2 is consistently above the threshold on Channel 1 and Channel 2</li> <li>See Figure 1(b) &amp; Figure 2(b)</li> </ul>
3	Clear multi-channel indication of the characteristic fault features; i.e. faulty	<ul style="list-style-type: none"> <li>After file#489</li> </ul>	<ul style="list-style-type: none"> <li>After file#489, Feature 2 is consistently above the</li> </ul>

	planet gear meshing with both the ring and sun gears.	<ul style="list-style-type: none"> <li>Filename: 'Day026_Hunting_SSA_20220114_145759.mat'</li> </ul>	threshold on Channel 1, Channel 2, and Channel 3 <ul style="list-style-type: none"> <li>Figure 1(b), Figure 2(b), and Figure 3(b)</li> </ul>
4	Confirmed trend of fault progression; i.e. a consistent increasing trend started from which file number/name.	An increasing trend is visually observed on <i>the moving averaged Feature 2</i> on Channel 2 after <b>File#352</b>	<ul style="list-style-type: none"> <li>See Figure 4(a)</li> </ul>
5	Confirmed trend of accelerated fault progression; i.e. a consistent exponential increasing trend started from which file number/name	An exponential evolution is visually observed on <i>the moving averaged Feature 2</i> on Channel 2 after <b>File#500</b>	<ul style="list-style-type: none"> <li>See Figure 4(b)</li> </ul>

## 2. Analysis Methods

The method is graphically illustrated in the figure below.



As seen in the figure, the signal of each channel, which is an angular resampled vibration signal, is processed using the automated cepstral editing procedure (ACEP)<sup>1</sup> to remove strong deterministic components. The processed signal is then further processed using the synchronous signal averaging (SSA) technique to improve the signal-to-noise ratio. Eight features are calculated from the SSA signal and then ranked based on the monotonicity metric. It was found that **Feature2, which is the kurtosis of the signal after the SSA process**, is the most effective for early detection as well as trend analysis. Moreover, it was also found that **Feature 7, which is the RMS of the squared envelope signal (SES) after the SSA process**, is also effective for early detection and trend analysis.

## 3. Illustrating Figures

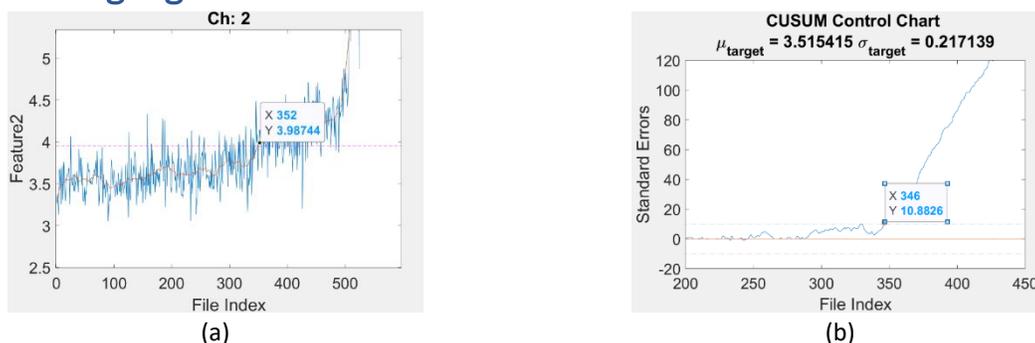
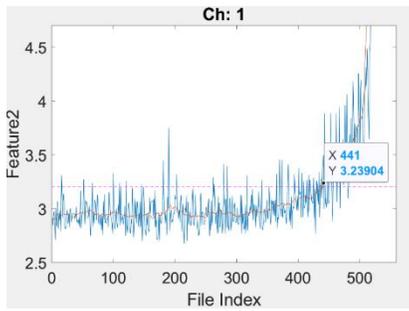
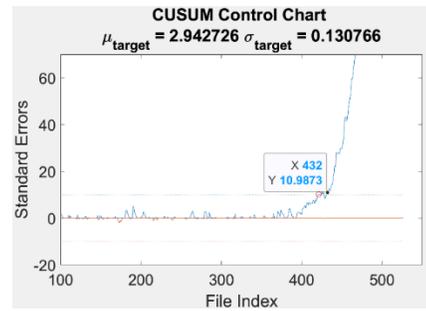


Figure 1: (a) The evolution of Feature 2 extracted from Channel 2, and (b) the corresponding CUSUM chart indicating the earliest detection at **File#346**

<sup>1</sup> A.P. Ompusunggu, and T. A. Bartic, "Automated cepstral editing procedure (ACEP) for removing discrete components from vibration signals", International Journal of Condition Monitoring, Vol. 6(3), pp. 56-61, 2016.

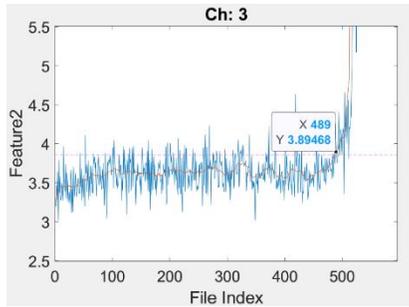


(a)

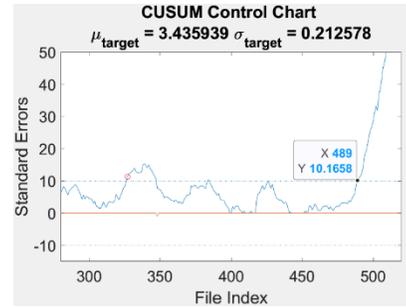


(b)

Figure 2: (a) The evolution of Feature 2 extracted from Channel 1, and (b) the corresponding CUSUM chart indicating the earliest detection at File#432.

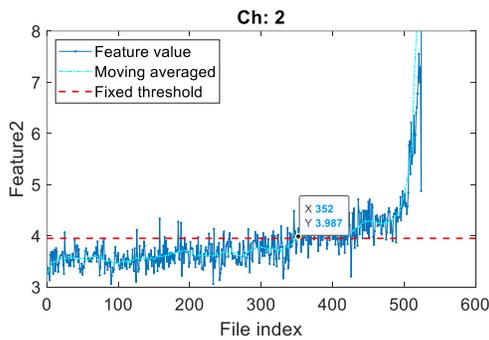


(a)

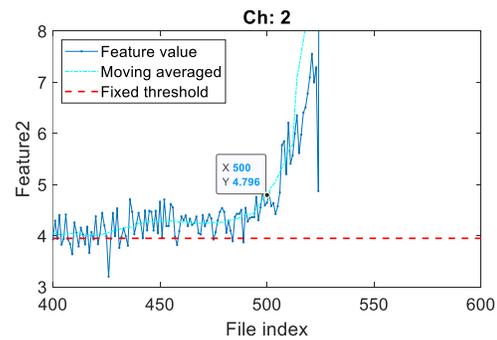


(b)

Figure 3: (a) The evolution of Feature 2 extracted from Channel 3, and (b) the corresponding CUSUM chart indicating the earliest detection at File#489.



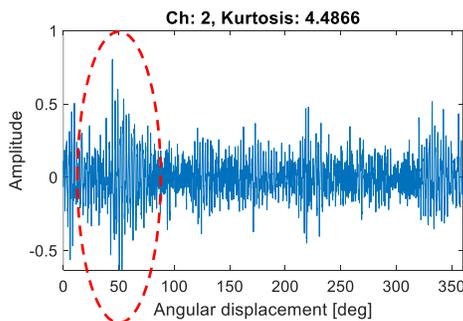
(a)



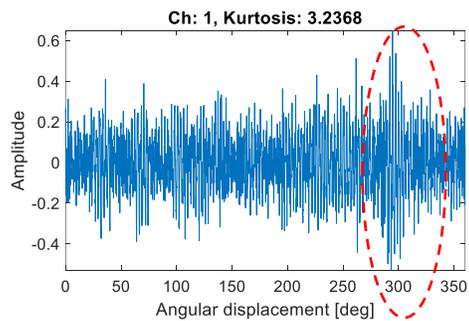
(b)

Figure 4 The evolution of Feature 2 extracted from Channel 2. (a) The indication of the start of fault Progression at File#352 and (b) The indication of the start of the exponential evolution at File #500.

## 4. Characteristic Fault Signatures of Early Detection



(a) Obtained from File#346



(b) obtained from File#432

Figure 5: Characteristic fault signal of the earliest detection by (a) Channel 2, and (b) Channel 1

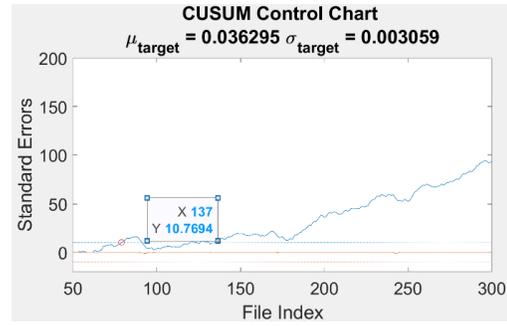
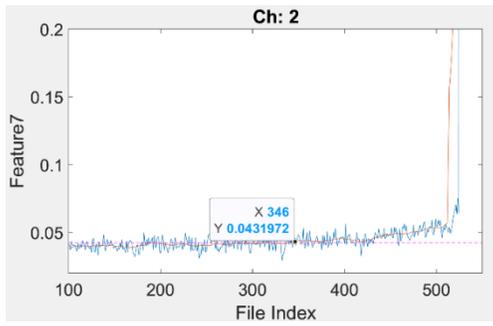


Figure 6 (a) The evolution of Feature 7 extracted from Channel 2, and (b) the corresponding CUSUM chart indicating the earliest detection at File#137.

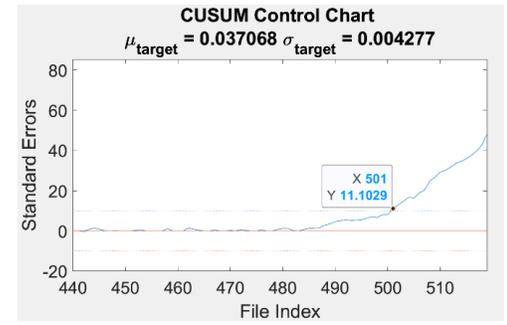
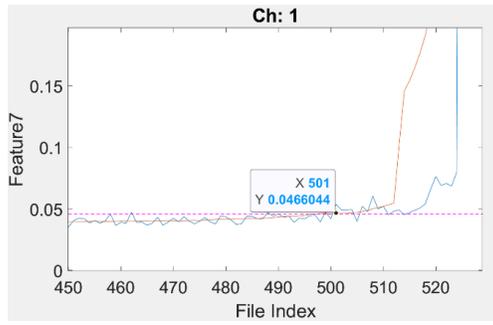


Figure 7 (a) The evolution of Feature 7 extracted from Channel 1, and (b) the corresponding CUSUM chart indicating the earliest detection at File#501.

## 5. Fault Progression Trending Curve

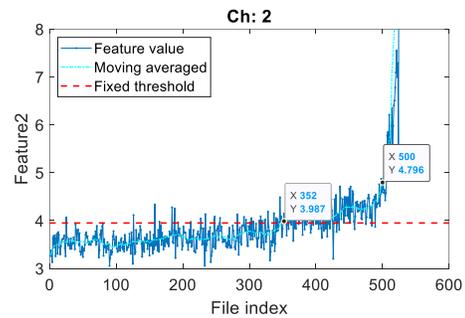
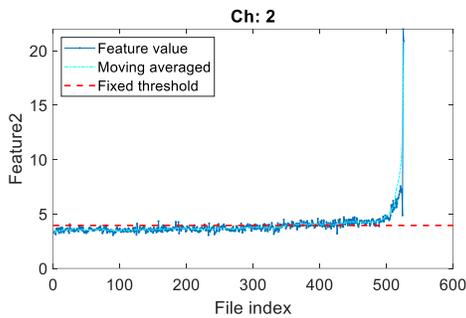
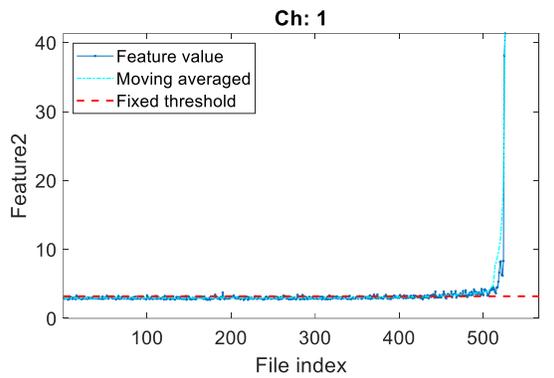
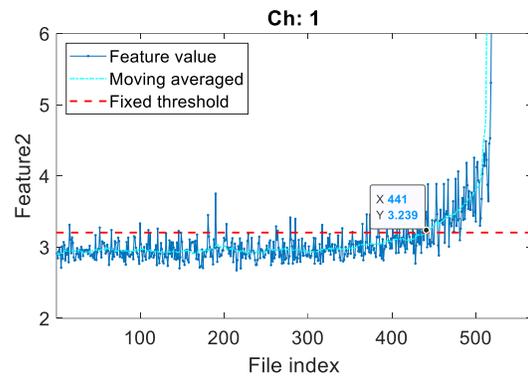


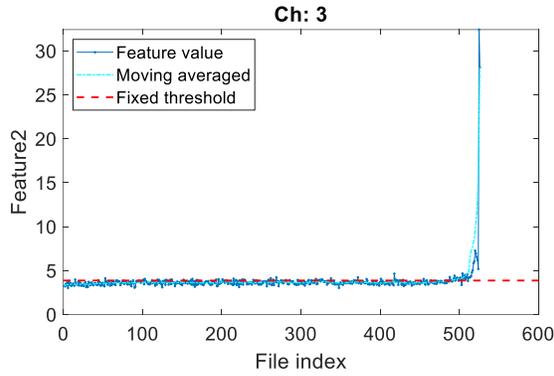
Figure 8 (a) Overall trend channel 2 (b) Zoomed-in trend channel 2  
 Figure 8 The trending curve for the planet gear fault progression indicating where the fault indicator (feature) started to increase consistently from file#352 and where the fault progression started to accelerate from file#500.



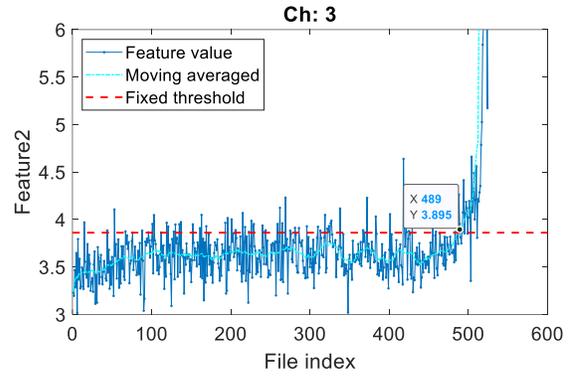
(a) Overall trend channel 1



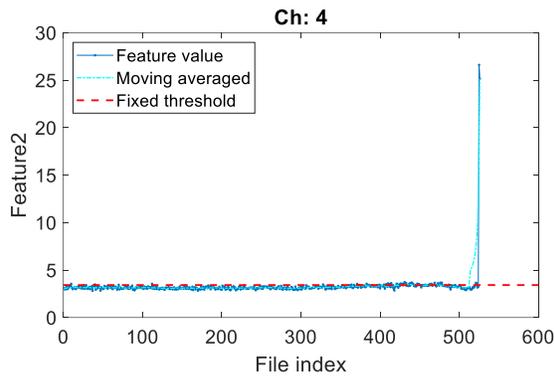
(b) Zoomed-in trend channel 1



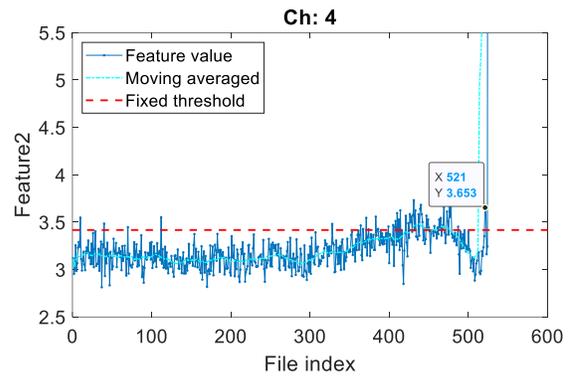
(c) Overall trend channel 3



(d) Zoomed-in trend channel 3



(e) Overall trend channel 4



(f) Zoomed-in trend channel 4

Figure 9 The trending curve for the planet gear fault progression from other channels

## 6. Description of Analysis Methods

### Fault detection method

The selected fault feature (Feature 2) calculated using the procedure described in Section 2 is then analysed using the CUSUM (or cumulative sum control chart) method to detect the change of the feature value indicating the progress of the fault. The CUSUM is a sequential analysis technique typically used for monitoring change detection. The CUSUM control chart is designed to detect small incremental changes in the mean of a process. In this analysis, we used the MATLAB signal processing toolbox for early fault detection using the CUSUM method<sup>2</sup>. The upper CUSUM threshold  $th$  is computed based on the mean value  $Mean$  and the standard deviation  $Std$  of the first 25 samples of Feature 2, according to this equation:  $th = Mean + c \times Std$ , where  $c = 10$ , is the control limit.

<sup>2</sup> <https://uk.mathworks.com/help/signal/ref/cusum.html>

## Fault trending method

As described in Section 2, eight features are calculated from the processed signal of each channel. These features are ranked based on the monotonicity metric to select the best feature for trending analysis. As degradation is typically an irreversible process (no self-healing), a relevant feature is one that has a strong correlation with time. The Monotonicity metric evaluates this trend information and shows which feature has degradation information of the asset. Since most machinery presents non-linear degradation, the Spearman correlation is chosen because it can transform the non-linear into a linear relationship between feature and time<sup>3</sup>. Thus, the monotonicity metric is taken as the absolute value of the Spearman correlation. As a result, the monotonicity metric ranges from 0 to 1, where a low value indicates a bad feature, on the contrary, a high value indicates a good feature.

Figure 10 shows a box plot of the monotonicity metric of all the 8 features extracted from 4 sensor channels. As seen in the figure, Feature 2, which is the kurtosis of the signal after the SSA process, demonstrates the highest monotonicity metric (the maximum and the mean). Besides, Feature 7 is considered the second best feature, because the minimum value of the monotonicity metric is higher than the other features.

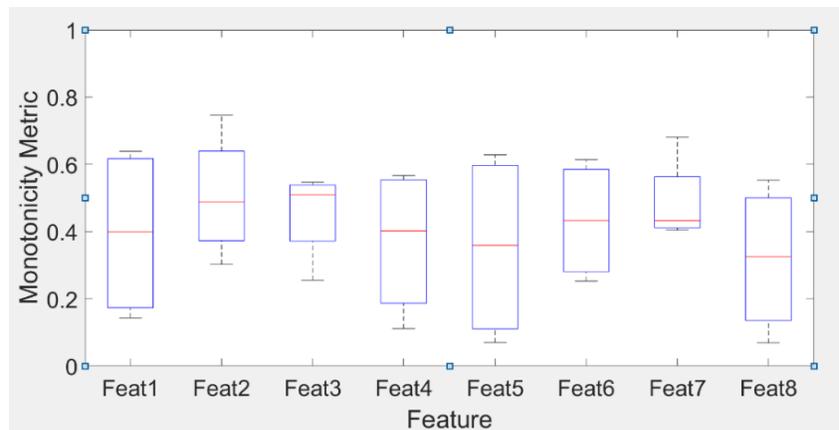


Figure 10: The monotonicity metric calculated using the Spearman correlation for all the 8 features.

For trending analysis purposes, we smoothened the selected feature (Feature 2) trend by using the moving average with a window size of 25 samples.

## 7. Supplement Information

N/A

<sup>3</sup> J. A. Carino, D. Zurita, M. Delgado, J. A. Ortega and R. J. Romero-Troncoso, "Remaining useful life estimation of ball bearings by means of monotonic score calibration," *2015 IEEE International Conference on Industrial Technology (ICIT)*, 2015, pp. 1752-1758