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Real time monitoring of the CNC process in a production environment- the data collection & analysis phase

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Abstract

For many years there has been considerable research from both an academic and industrial perspective into the monitoring and control of CNC machining processes, and progress has been well documented. It is widely acknowledged within the CIRP community that collection of information into the performance of material cutting processes is a worthwhile research topic, and this is mirrored in the work of the Scientific Technical Committee-Cutting (STC-C) and other Scientific Technical Committees.
This work has been continued by the consortium engaged in the REALISM project, an EU-FP7 funded project which is investigating the use of sensor fusion in a real time production environment, to monitor CNC tool wear through the use of three sensor technologies- Force, Acoustic Emission and Vibration. However, the real work of the project consortium will be in the analysis and interpretation of the data from the collated fusion of the deployed sensors- and the intelligent interrogation of this sensor information. The sensor deployment strategy of this project was outlined in a presentation, poster and paper presented at the 2014 CIRP ICME conference and this current paper provides an update on the ongoing work.
An overview is provided in this paper of the challenges that have been overcome as part of the REALISM project, and a brief overview of the initial verification trials that were undertaken on the deployment of the sensors. Further results will also be presented that show promising initial sensor data, which shows conditions leading to Catastrophic Tool Failure (CTF).

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Keywords: Machining; Tool wear monitoring; Process control; Catastrophic tool failure.

1. Introduction

As is well documented, there have been many years of investigation into the use of physical emissions from the CNC machining process to evaluate the performance of the cutting operation. Such has been the extent of the investigations for in excess of forty years that there has been a number of opportunities for the research community, both academic and industrial, to take stock and publish extensive state of the art snapshots of the current state of the art in this area. The most recent of these was by Teti *et al* [1] in 2010 in a CIRP keynote paper. Given the fact that previous state of the art reviews of the advances in the field were undertaken in 1995 by Byrne *et al* [2], in 1988 by Tonshoff *et al* [3], in 1983 by Tlusty & Andrews [4] and as far back as 1976 by Micheletti [5], one can appreciate the breath and range of interest in this area.

During the research and experimentation through the years, many process variables, failure modes and data interrogation methods have been employed in an attempt to determine how tool wear in the machining operation can be monitored and evaluated, in real time and *in situ* to provide accurate feedback to the machine operator as to the condition of the operation.

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Early studies tended to concentrate on the directly and easily measurable characteristics within the machine operation such as spindle motor current [6]. However, it was determined later that the various other energy releases from the machining process would offer more valuable information about the process than those directly measurable from the machine.

With this mindset, research focused on the physical emissions emanating from the cutting zone that were measurable in immediate cutting environment, or emissions that were transferred from the process to close structures within the machine tool. The measurable phenomena that were quickly identified by the research community in this regard were process temperature [7,8], force [9,10], ultrasonic emissions [11], work piece irradiation [12], audible sound energy [13-15] and acoustic emissions [16-18]. In addition to this work, there has also been extensive research into the use of multiple sensors in a fusion configuration [19,20]. Driven by developments in this area, significant work has been undertaken into the analysis of the signal features from the sensors [21,22], and the use of neural networks to analyze the resultant information [23-25].

In addition to the literature available from the industrial and academic research community there have been a number of large scale collaborative projects investigating the feasibility of sensor monitoring of tool wear, such as ADACOM [26], IFACOM [27] and SOMMACT [28].

The participants in the REALISM [29] project have been involved for many years in research into the evaluation of all the above mentioned process phenomena, and have collectively arrived at the conclusion that the chosen process emissions in the REALISM project contain the most worthwhile information as to the performance of the process.

The process emissions that were identified by REALISM to be analysed include;

- Acoustic Emission (AE_{rms})
- Vibration ($V_xV_yV_z$)
- Force ($F_zF_yF_x$)

An overview of the REALISM project plan was given at the 2014 CIRP ICME conference [30].

2. Overview of the REALISM project

REALISM is an FP7 funded research project with participants across a number of member states within the European community. The consortium partners are listed in Table 1.

Table 1. The REALISM consortium

Name	Country	Participant type
Schivo Precision	Ireland	SME
Waterford IT	Ireland	RTD
IDT Solutions	Norway	SME
Warsaw University	Poland	RTD
Tulino CTM	Italy	SME
University of Naples	Italy	RTD
Gjovic University	Norway	RTD

2.1 The consortium work package breakdown for members

The REALISM project consortium work packages are broken down as detailed in figure 1 below.

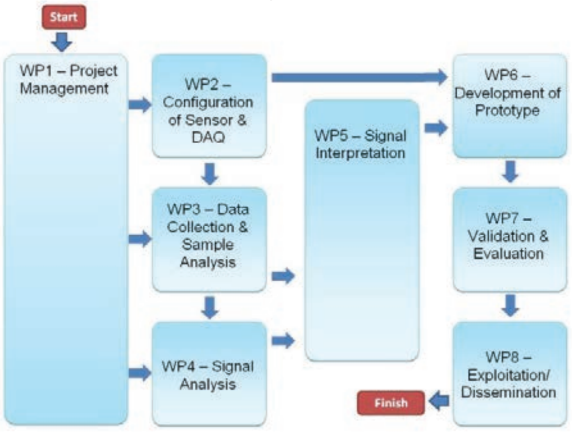

Figure 1. Realism project work package overview

3. Overview of the deployment of the sensor system agreed by the REALISM project consortium

It was agreed that the sensors to be deployed on CNC machine tools for the investigation phase would include an AE sensor, a vibration sensor and a force sensor. The sensor types that were agreed are outlined in Figure 2:

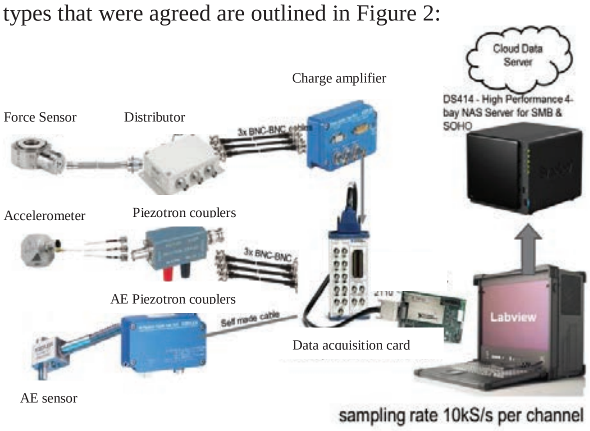

Figure 2. The realism sensor configuration.

It was agreed that the sensors would be deployed on a machine within Schivo Precision based in Waterford, Ireland. It was determined that the best machining configuration was a turning configuration, given that most vertical and horizontal machining operations utilize tools with multiple cutting surfaces. However, turning operations on a lathe typically employ single-point cutting or two-point drilling.

This means that the cutting tool wear is less complicated in a turning configuration and is simpler to interrogate, as there are less variables in terms of cutting/material interfaces during a real time production environment.

It was decided that the sensor installation would be undertaken on a Mazak Quickturn Nexus 200II, shown in Figure 3.

Figure 3. Mazak quickturn 200 nexus lathe at schivo

4. Overview of the Sensor installation on the Mazak Quick turn Nexus 200

The installation of the sensors was simple in the case of the AE sensor and the accelerometer, in that these sensors were installed on the machine turret, as illustrated in Figure 4.

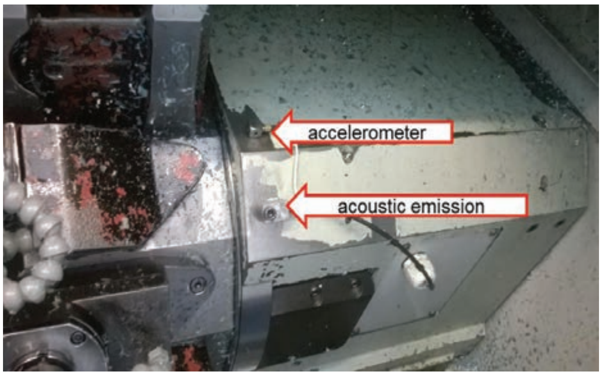

Figure 4. Position of installation sites of acoustic emission & vibration sensors.

However, the installation of the force sensor proved to be more problematic. The force sensor on the machine was intended to be at the interface of the turret with the main machine body. However, it was discovered that the particular model of Mazak lathe is fitted with a slideway turret, which meant that this installation location was not feasible. We therefore identified a number of locations within the machine through which forces would likely be transmitted, but in discussion with the consortium partners realized that the transmission paths for these forces through these locations would not provide worthwhile sensor information.

With this in mind we agreed to insert the force sensor into the structure of the machine, by drilling a hole into the substructure of the machine (at the risk of compromising the structural integrity of the machine). The final location of the force sensor is shown in Figure 5

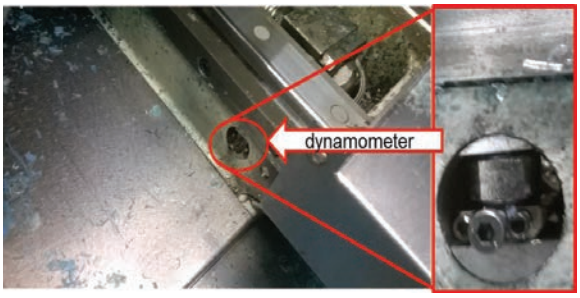

Figure 5. Location of the force sensor in a specially drilled pocket.

5. Presentation of the results from the initial cutting trials.

Once the initial issues with the sensor installation and configuration were overcome, we were able to commence cutting trials on the machine.

These cutting trials were undertaken on the machine in controlled conditions using billets of 316SS. For varying cut depths, comparative trials were undertaken with new and worn cutting tools. Table 2 below outlines the cutting configuration and parameters for this trial:

Table 2. Cutting parameters of verification trials

Machine	Mazak Nexus 200
Operation	Single point turning
Cutting Insert Type	Sandvik Carbide WNMG 08 04 08- QM
Work piece material	316ss
Constant surface speed rate (Vc)	100m/min
Feedrate (Fn)	0.225mm/rev
Cut length	85mm
Original work piece diameter	57mm

Analysis was undertaken on each of the 7 individual sensor signals- F_x, F_y, F_z, V_x,V_y,V_z and AErms - and the correlations are illustrated in Figures 6-8 below.

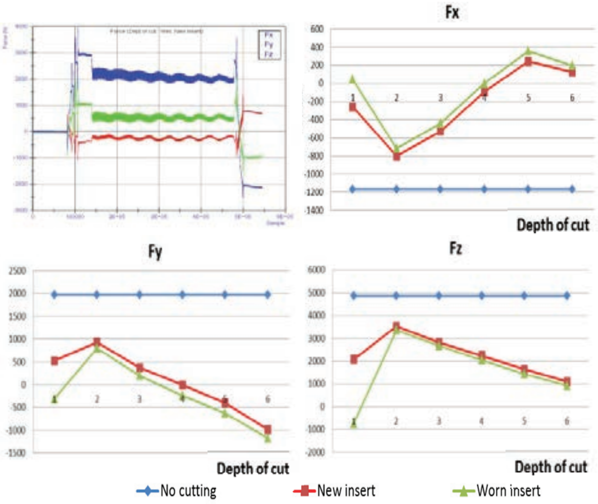

Figure 6. Plot of the three cutting forces (fx, fy, fz) versus depth of cut for a new and worn insert and when no cutting is taking place.

The plots show that the cutting forces are affected by the cut depth and that there is a change in magnitude between the new and worn insert. These results correlate with the expected outcome. The results of the vibrations (Vx, Vy & Vz) versus depth of cut for a new and worn insert are given in Figure 7. Plots of the vibrations when no cutting is taking place are also shown and were found to have a negligible effect on the operational vibrations.

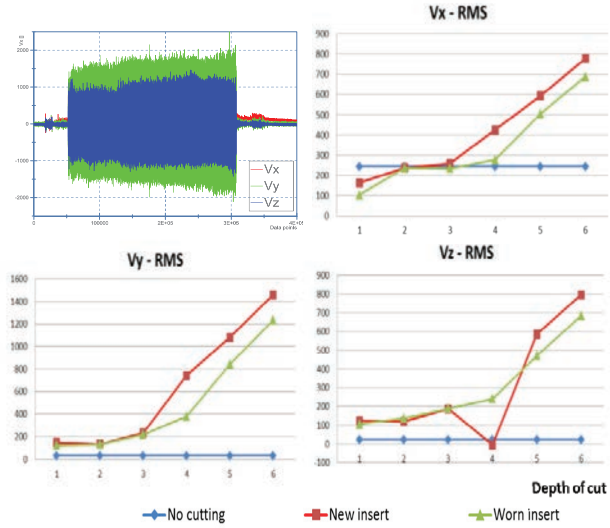

Figure 7. Plot of vibration (vx, vy, vz) versus depth of cut for a new and worn insert and when no cutting is taking place.

The plots show that the vibrations are affected by the cut depth and that there is a change in magnitude between the new and worn insert. These results correlate with the expected outcome. The results of the acoustic emissions (AErms) versus depth of cut for a new and worn insert are given in Figure 8. A plot of acoustic emissions when the machine is in operation but no cutting is taking place is also shown.

Figure 8. Plot of acoustic emission (rms) versus depth of cut for a new and worn insert and without cutting.

The plot shows that acoustic emissions can be detected at depths of cut about 3mm for both the new and worn insert. Below this, the magnitudes of the emissions are not sufficiently distinguishable between the emissions when no cutting is taking place. Adjustments were made to the AE sensor to improve signal gain.

Figure 9 shows the images of an unused (A) and of the new (B) and worn insert (C) which were used for the cutting operations. The profile of the tip and allows for wear comparison and quantification. Figures 9(C) shows that there is sufficient wear of the tip to have an effect on the machining parameters and sensor data.

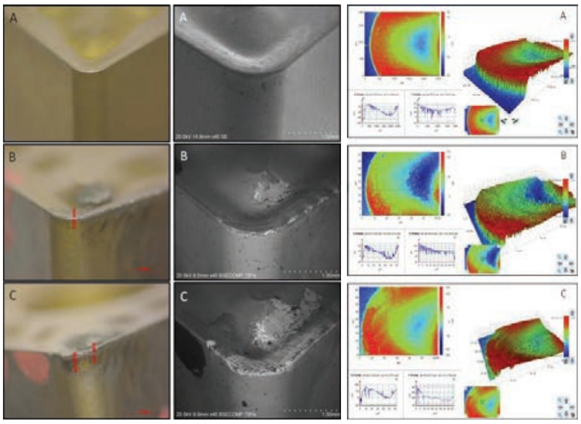

Figure 9. Images of tip using optical microscopy, scanning electron microscopy and white light interferometry.

Figure 10 shows the characterisation of the workpiece surface after the cutting tests were completed for the new (a) and worn (B) insert. This shows that the workpiece surface profile is affected by tool wear.

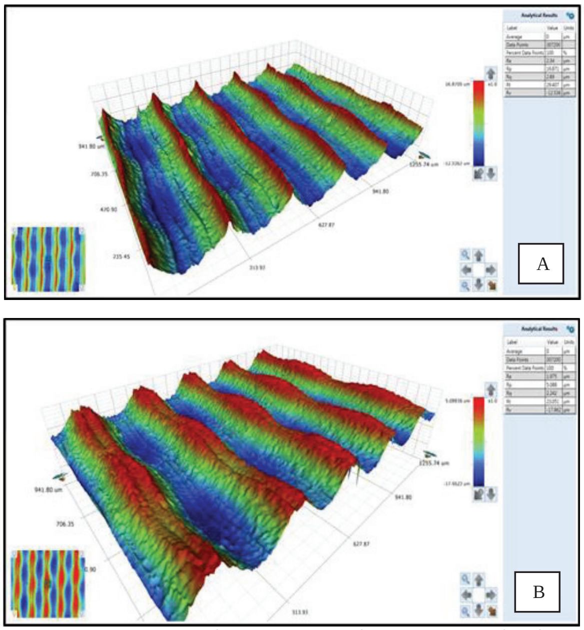

Figure 10. White light interferometry images of the workpiece surface for a new (a) and worn (b) insert.

Initial results show that the force and vibration sensor are giving results in line with expectations. The AE sensor signals are not sufficiently distinguishable between the emissions when no cutting is taking place. Adjustments were made to the AE sensor to improve signal gain. The characterisation techniques have been established and allow for correlation with the sensors data. The data acquisition system duplicates files on the cloud server and can be accessed by all consortium members.

6. M-code and G-code programming

For effective signal data analysis, it was imperative to distinguish between machine operation (tool changes, turret movements, coolant on/off) and machine cutting (Cutting Feed). To achieve this, the CNC controller had to be given additional functionality with the expansion of machine codes (M-codes) using a bolt-on M-code module. The additional M-codes allowed the machine programmer to implement G-code programming to switch on/off analogue relays and digital signals (logic 0 or 1) to control data acquisition parameters. This is used, for example, to give the DAQ and LabVIEW software information on the tool number through the use of a binary table system with 3M-Code inputs as described in Table 3.

Table 3. M-Code outputs from Mazak Machine to DAQ

Description	M-Codes	Binary I/P to DAQ
File Acquisition start/stop	M8/M9	Analogue
Tool No 1	402	001
Tool No 2	403	010
Tool No 3	402,403	011
Cutting Feed Start	400	101
Cutting Feed Stop	401	110
Tool Change	401,402, 403	111

7. Overview of data taken from the TCM system in first production trials

With the sensor system and M-codes fully operational, controlled cutting tests were undertaken at the beginning of May 2015. This testing comprised of cutting high carbon tool steel continuously over an 8-hour shift and evaluating the tool condition with an optical Zeiss microscope. Experimental conditions are given in Table 4. The sample rate is 10kHz.

Table 4. Operational conditions of ctf instances.

Name	Workpiece start diameter (mm)	Depth of cut (mm)	Cut length (mm)	Feed rate (mm/rev)	Surface speed (Vc) (m/min)
Figure 9	113	5	149	0.4	260
Figure 10	72	4	149	0.3	195
Figure 11	100	4	149	0.3	195

During these trials a number of instances of Catastrophic Tool Failure (CTF) occurred (Figure 11).

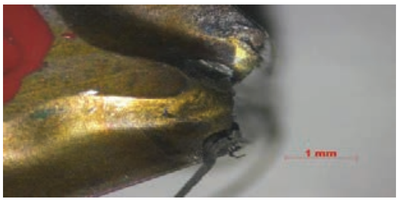

Figure 11. Insert exhibiting critical tool failure (ctf).

Figures 12, 13 & 14 show the sensor signals detected in the lead up to the occurrence of CTF.

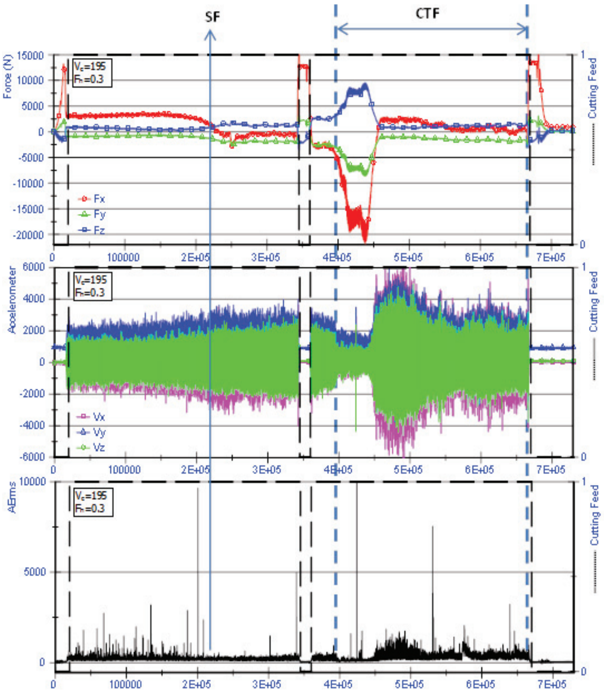

Figure 12. Sensor information from ctf, instance 1

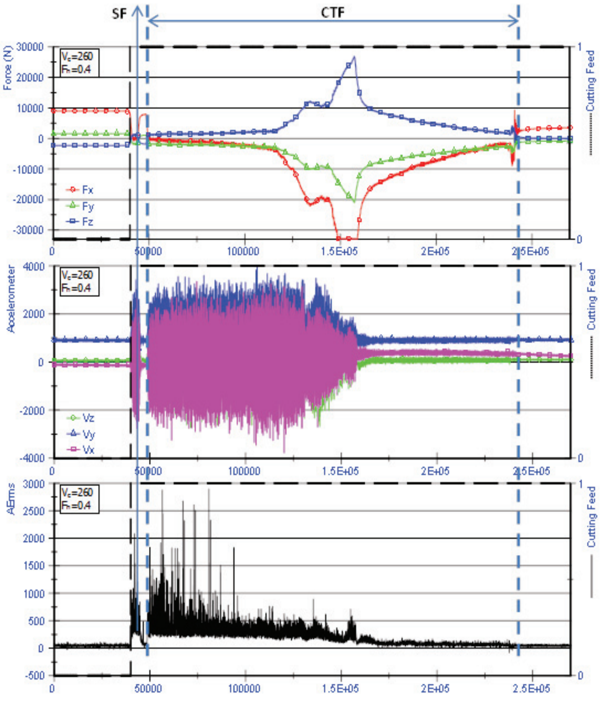

Figure 13. Sensor information from ctf instance 2

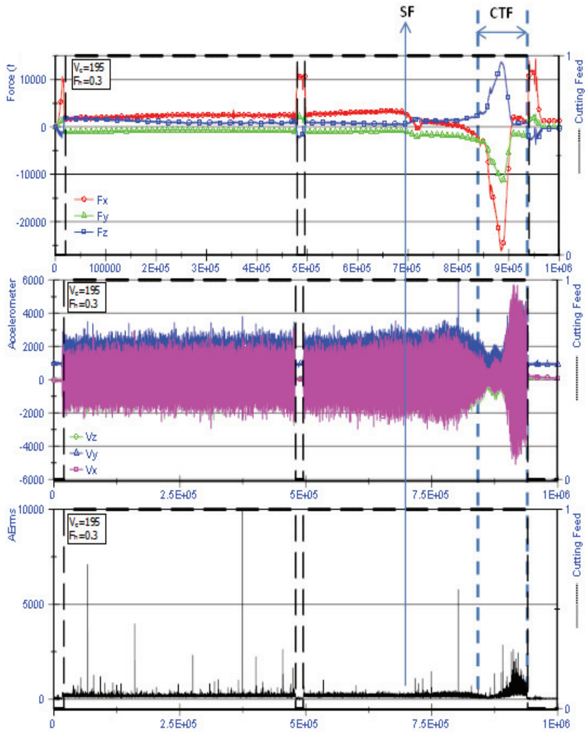

Figure 14. Sensor information from ctf instance 3

In the above figures, the incidence of CTF occurs in the band indicated as "CTF". There is a consistent anomalous signal feature (SF) indicated by the "SF" band in advance of the CTF event. This signal feature is most prevalent in the three axes of the force sensor, and lasts for approximately 2500ms. However, our examination of the corresponding sensor signals indicated that there is a pattern in this region that is also unique and worth further investigation.

8. The Data analysis

A neural network approach is being taken to the analysis of the results from the sensors. The approach taken is the use of a number of signal features from the sensors. The signal features are correlated against the degree of tool wear as a percentage of the tool life. This approach is being presented separately in the conference in an overview paper provided by the research staff at the University of Naples Federico II. The approach that has been taken in this regard is the interpretation of a number of signal features as will be outlined separately within the project dissemination.

9. Conclusions

As outlined in this paper, the initial deployment of the sensors has proven successful, with good correlation between the sensor signals from a known worn condition and a known good cutting condition.

As the sensors were deployed on a standard production machine, rather than in a laboratory environment, there were a number of challenges encountered during the initial setup phase. However, these were overcome and the system as demonstrated in this paper is now fully operational.

There are encouraging results from the sensor system both at the initial deployment stage. Furthermore, the CTF detection potential outlined in Figures 12, 13 & 14 suggest that the deployed sensor configuration could give extremely useful information regarding the machining operation.

The deployment of the sensors on a real-time production machine has proven that the sensor configuration works outside a laboratory environment. The work initially outlined in this paper serves to prove the belief that sensor fusion is a worthy method, through which real-time analysis can be undertaken on a machining operation in a real-time production environment, once a correctly configured sensor system is used.

The sensor information outlined in section 7 of this paper is promising in that initial observations suggest that there are signal features that may provide advance warning of CTF.

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