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Digital Twin Based Online Material Defect Detection for CNC-Milled Workpieces

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Abstract

Achieving reliable lot size one compatible and adaptable online quality monitoring for CNC-milled workpieces remains elusive yet. To address this challenge, our approach aims to bridge the current gap in research by developing a cost-effective and reference-independent monitoring concept for material defect detection in CNC-machined parts. This paper presents a novel digital twin-based method, utilising machining vibrations and a g-code-based encoding of the cutting process. The objective is to detect material defects, such as blowholes, without the need for individual workpiece references. The proposed method aims to reduce barriers to entry, minimise waste, and enhance machine productivity by enabling automated early online quality control. To develop and validate the model, we generate a new dataset combining machining vibration with technological context data such as chip-shape. We demonstrate the feasibility and potential of the approach in a job shop setting on a 3-axis CNC mill.

Keywords: Online process monitoring; Material defect detection; Digital Twin; Lot size one; Vibration monitoring

1. Introduction

The manufacturing industry is undergoing a paradigm shift, transitioning from a focus on 'responsiveness' to a 'market-of-one', deemed 'Mass Individualisation' [1] or 'Mass Personalisation' [2]. This entails the production of custom-made products while maintaining the low unit costs traditionally associated with mass production. In response, there has been a global push towards smart manufacturing characterized by autonomous operations enabled by advanced sensing, data processing, and decision-making technologies. [3, 4].

Within this context, reducing lot sizes in job-shop settings becomes imperative, and additive manufacturing (AM), particularly 3D printing, emerges as a promising solution due to its autonomy and versatility. However, despite its advantages, AM still falls short compared to traditional techniques like CNC milling in aspects such as dimensional accuracy, mechanical properties, material variety, and surface quality [5, 6, 7]. CNC milling, therefore, remains pivotal, presenting not only significant potential but also high necessity for optimisation due to its complex nature of underlying processes that result in lower process resilience and robustness compared to AM.

Nomenclature

CNC	Computerised Numerical Controled (machine tool)
AM	Additive Manufacturing
CCC	...

A monitoring system that utilises deep process context (e.g. technological, geometric, or material property data) to generate reference agnostic (= lot size one capable) process status insights, would ready CNC mills for the Mass Personalisation paradigm shift.

Such a workpiece-centered monitoring system which detects material defects or user (=operator) error (e.g. wrong material,

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or part clamping error) during normal machining can increase process efficiency & reliability, reduce waste, and enable higher product quality.

To achieve economic efficiency and general market accessibility such a system must be easy to integrate, be machine agnostic, and be relatively low cost.

2. Related work

state of the art (1,5seiten)

Predominantly, CNC monitoring is focused on tool condition monitoring, particularly detecting tool wear and breakage, ensuring surface finish quality, including mitigating chatter, and monitoring machine health for predictive maintenance purposes [8, p.2727].

The following sensors are used and listed with their general purpose below: Table 1 lists employed sensors and rates them by investment cost and by information value.

Table 1. Sensors according to signals and properties[according to 8, p.2725]

Sensor	Level of investment cost	Extent of signal accuracy and information value
Dynamometer	•••••	•••••
Accelerometer	••••	•••
AE	••••	•••
Current/power	•	•
Temperature	•••	••
Sound	•	•

2.1. Related scientific work

Matta's Grey-1 model as shown in their paper [9] demonstrates AM process monitoring on fused layer deposit 3D printers, based on an automated deep process understanding. They trained a multi head transformer model on labeled images, such as: extrusion speed, layer thickness and hotend temperature. They are able to detect extrusions errors (which translate in to material defects), or adjust printing parameters fully autonomously for unseen material.[9]

This study serves as a substantial inspiration and influence for the present work.

Another notable study [10] investigates the cutting forces measured by a (6-axis) dynamometer in micromanufactuirng of Ti6246 alloy by comparing them with theoretical calculted forces, to detect material defects such as blow holes. This aproach is in theory lot size one capable because the force measurement is not compared to one of a part prior, but is rather based on experimental measurements and a geometric physically-based process simulation. It is concluded that the accuracy of the calculated force and the insufficient change of amplitude while machining a defect were to low to achieve automated detection. [10, p.169]

While dynameter force measurements offer greatest signal accuracy and information value due to their direct measurement methode and process proximity [11], they are the most expensive (~ 60.000€) and usualy difficult to setup and not feasable for production envirnoments.

Sensor products employed in research:

- Acoustic Emission via Optimizer 4D by Quass; powerful AE monitoring employed in tool condition monitoring and tested (sci) on chatter detection (Szulewski.Sniegulska-Gradzka2017)

- multi axis Force Dynanometers by Kistler; most direct process monitoring (most powerful); material defects monitoring in micro milling Ti(Pfirrmann.Baumann.ea2021)

- Contact Microphone (Gitarrenabnehmer) for chatter detection

3. Aproach

(vorgehen + prinzipielle aufbau/Konzept)
- welche physikalische grsse? vibration
- kontext architektur (feature)
- schaubild design

4. Implementation

- full design from approach transform to proof of concept
- in python, auf emco, DoE...
- experimental setup

5. Validation

...and evaluation

6. Conclusion

and futere recommendation (halbe seite)

Zitiertest...
[12, 13, 14]
[13]
[14]
[15]
[5]

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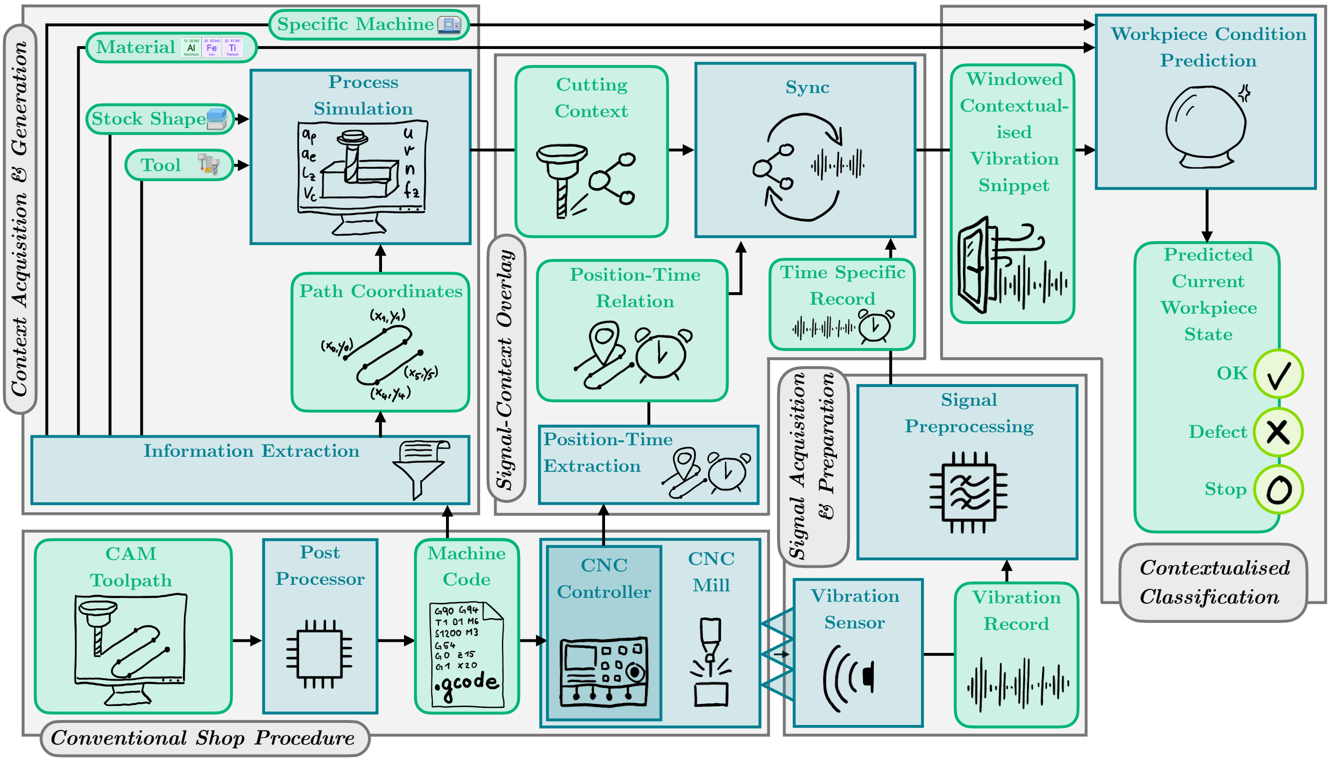

Fig. 1. High-Level Concept

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