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RESEARCH ARTICLE

Hidden Markov Model based Digital Twin Construction for Futuristic Manufacturing Systems

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Abstract

Abstracts should be 250 words. It must be able to stand alone and so cannot contain citations to the paper's references, equations, etc. An abstract must consist of a single paragraph and be concise. Because of online formatting, abstracts must appear as plain as possible.

Impact Statement

Provide a 200 word impact statement that summarises the significance of the work, so that it can be quickly grasped by a wide audience (including industry, government and wider academia).

1. Introduction

The aerospace community has introduced a system engineering concept called digital twin, which refers to an exact mirror image of a real-life aspect (e.g., flying of a spacecraft) in the cyberspace using the multi-scale, multi-physics, and probabilistic simulation that is aided by the sensor updates and historical data (Glaessgen and Stargel 2012). This has inspired the research community of the futuristic manufacturing systems (e.g., Industry 4.0, smart manufacturing, and connected factory). As such, the digital twins of manufacturing aspects are expected to populate the systems (e.g., cyber-physical systems) that are needed for functionalizing the futuristic manufacturing systems (Grieves and Vickers 2017; Ullah 2019). The research on digital twin construction reports its myriad interplays with various aspects of futuristic manufacturing systems. Some of the recent articles are described below.

Nevertheless, from the viewpoint of contents, the digital twins can be categorized into three categories, namely, object twin, process twin, and phenomenon twin (Ullah, 2019). An object twin is the computable virtual abstraction of the geometrical and topological structures of a product (e.g., a gear) or a facility (a machine tool, an assembly line, and so forth). A process twin is a computable virtual abstraction of a process or production plan (e.g., scheduling for machining a part at different workstations spread in different factories, a bill of materials, and so forth). On the other hand, the computable virtual abstraction of a manufacturing phenomenon (e.g., the phenomena related to material removal process, namely, cutting force, tool wear, cutting temperature, workpiece deformation, surface roughness, chatter vibration, and so forth) is called a phenomenon twin. The three categories of digital twins must populate the systems (e.g., cyber-physical systems) underlying futuristic manufacturing systems, as mentioned above.

Section 2 is organized in three subsections to describe the methodology showing how to construct a hidden Markov model for an arbitrary time series. Section 3 describes a case study where the methodology described in Section 2 is applied to create the digital twins of the surface roughness of ground surface (i.e., the workpiece surface generated by successive grinding operations).

2. Methodology

This section describes a methodology showing how to construct a hidden Markov model using the information of an arbitrary time series. For the sake of better understanding, this section first describes the fundamental idea, which is followed by the mathematical formulations and algorithms, respectively.

2.1. Fundamental Idea

The fundamental idea means here a somewhat informal description of the hidden Markov model and its relationship with a time series.

3. Data and Numerical Models

The computing power of hidden Markov models has been playing an important role in studying the complex phenomena underlying design and manufacturing. For example, Liao et al. (2016) have developed a heuristic optimization algorithm using hidden Markov model coupled with simulated annealing for condition monitoring of machineries. Li et al. (2018) have developed a data-driven bearing fault identification methodology using an improved hidden Markov model and self-organizing map. Mba et al. (2018) developed a hidden Markov model based methodology for condition monitoring of gearbox. Zhang et al. (2018) developed a methodology for predicting the residual life of the rolling machine elements using hidden Markov model. Xie et al. (2016) described the hidden Markov model based methodology for recognizing the machining states ensuring the safe operations. Bhat et al. (2016) developed a hidden Markov model based tool condition monitoring methodology ensuring the economical usages of cutting tools. Liao et al. (2006) developed a grinding wheel condition monitoring methodology where a hidden Markov model based clustering approach was used to recognize the patterns found in the acoustic emission signals. Cai et al. (2018) developed a methodology using hidden Markov model to identify the energy efficiency states while removing materials by milling ensuring eco-friendly machining operation. Kumar et al. (2018) integrated hidden Markov model with polynomial regression for predicting the useful life of cutting tools. Nevertheless, this case study shows how to apply the hidden Markov model (presented in Section 2) for constructing a phenomenon twin of surface roughness. The description is as follows.

Grinding is a widely used material removal process that helps remove materials from the surfaces of the objects made of difficult-to-cut materials (e.g., stainless steels, ceramics, and so forth) ensuring a high surface finish. In grinding, a complex microscopic interaction between the abrasive grains attached on the circumferential surface of grinding wheel and work-surface takes place (Ullah, 2019).

4. Equations

Equations in LaTeX can either be inline or on-a-line by itself. For inline equations use the `$...$` commands. Eg: The equation $H\psi = E\psi$ is written via the command $H\psi = E\psi$.

For on-a-line by itself equations (with auto generated equation numbers) one can use the equation or eqnarray environments *D*.

$$\mathcal{L} = i\psi\gamma^{\mu}D_{\mu}\psi - \frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} - m\psi\psi \tag{1}$$

where,

$$\begin{aligned} D_{\mu} &= \partial_{\mu} - ig\frac{\lambda^{a}}{2}A^{a}_{\mu} \\ F^{a}_{\mu\nu} &= \partial_{\mu}A^{a}_{\nu} - \partial_{\nu}A^{a}_{\mu} + g f^{abc}A^{b}_{\mu}A^{a}_{\nu} \end{aligned} \tag{2}$$

Notice the use of `\nonumber` in the align environment at the end of each line, except the last, so as not to produce equation numbers on lines where no equation numbers are required. The `\label{}` command should only be used at the last line of an align environment where `\nonumber` is not used.

$$Y_{\infty} = \left(\frac{m}{\mathrm{GeV}}\right)^{-3}\left[1 + \frac{3\ln(m/\mathrm{GeV})}{15} + \frac{\ln(c_2/5)}{15}\right] \tag{3}$$

The class file also supports the use of `\mathbb{}`, `\mathscr{}` and `\mathcal{}` commands. As such `\mathbb{R}`, `\mathscr{R}` and `\mathcal{R}` produces $\mathbb{R}$, $\mathscr{R}$ and $\mathcal{R}$ respectively.

5. Figures

As per the LaTeX standards eps images in `latex` and pdf/jpg/png images in `pdflatex` should be used. This is one of the major differences between `latex` and `pdflatex`. The images should be single page documents. The command for inserting images for latex and pdflatex can be generalized. The package that should be used is the graphicx package. See Figure 1.

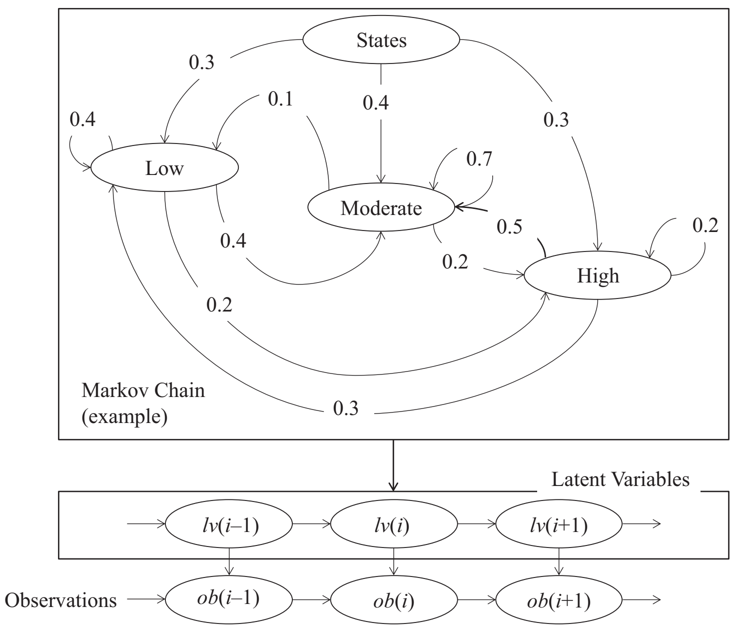

Figure 1. The concept of hidden Markov model.

Table 1. Tables which are too long to fit, should be written using the “table*" environment as shown here

	Element 1			Element 2[1]		
Projectile	Energy	σ_{calc}	σ_{expt}	Energy	σ_{calc}	σ_{expt}
Element 3	990 A	1168	1547 ± 12	780 A	1166	1239 ± 100
Element 4	500 A	961	922 ± 10	900 A	1268	1092 ± 40

[0]**Note:** This is an example of table footnote this is an example of table footnote this is an example of table footnote this is an example of table footnote this is an example of table footnote
[1]This is an example of table footnote

6. Tables

Tables can be inserted via the normal table and tabular environment. To put footnotes inside tables one has to use the additional “fntable" environment enclosing the tabular environment. The footnote appears just below the table itself. See Table 1.

7. Cross referencing

Environments such as figure, table, equation, align can have a label declared via the `\label{#label}` command. For figures and table environments one should use the `\label{}` command inside or just below the `\caption{}` command. One can then use the `\ref{#label}` command to cross-reference them. As an example, consider the label declared for Figure 1 which is `\label{fig1}`. To cross-reference it, use the command `Figure \ref{fig1}`, for which it comes up as “Figure 1". The reference citations should used as per the "natbib" packages. Some sample citations: Alam and Saddik (2017); Chui et al. (2013); Oliveira et al. (2017); Talkhestani et al. (2018).

8. Lists

List in LaTeX can be of three types: enumerate, itemize and description. In each environments, new entry is added via the `\item` command. Enumerate creates numbered lists, itemize creates bulleted lists and description creates description lists. List in LaTeX can be of three types: enumerate, itemize and description. In each environments, new entry is added via the `\item` command. Enumerate creates numbered lists, itemize creates bulleted lists and description creates description lists.

1. This is the 1st item
2. Enumerate creates numbered lists, itemize creates bulleted lists and description creates description lists.
3. Numbered lists continue.

List in LaTeX can be of three types: enumerate, itemize and description. In each environments, new entry is added via the `\item` command.

- This is the 1st item
- Itemize creates bulleted lists and description creates description lists.
- Bullet lists continue.

9. Conclusion

Some Conclusions here.

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Competing interests. A statement about any financial, professional, contractual or personal relationships or situations that could be perceived to impact the presentation of the work — or 'None' if none exist

Data availability statement. A statement about how to access data, code and other materials allowing users to understand, verify and replicate findings — e.g. Replication data and code can be found in Harvard Dataverse: `\url{https://doi.org/link}`.

Ethical standards. The research meets all ethical guidelines, including adherence to the legal requirements of the study country.

Author contributions. Please provide an author contributions statement using the CRediT taxonomy roles as a guide `\url{https://www.casrai.org/credit.html}`. Conceptualization: A.A; A.B. Methodology: A.A; A.B. Data curation: A.C. Data visualisation: A.C. Writing original draft: A.A; A.B. All authors approved the final submitted draft.

Supplementary material. State whether any supplementary material intended for publication has been provided with the submission.

References

Alam, K. M. & Saddik, A. E. (2017). C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems. *IEEE Access*, 5:2050–2062.

Bhat, N. N., Dutta, S., Pal, S. K., & Pal, S. (2016). Tool condition classification in turning process using hidden Markov model based on texture analysis of machined surface images. *Measurement*, 90:500–509.

Cai, Y., Shi, X., Shao, H., Wang, R., & Liao, S. (2018). Energy efficiency state identification in milling processes based on information reasoning and Hidden Markov Model. *Journal of Cleaner Production*, 193:397–413.

Chui, M. W., Feng, Y. Q., Wang, W., Li, P. L., & Li, Z. C. (2013). Numerical Simulation of Rough Surface with Crossed Texture. *Applied Mechanics and Materials, 321–324*, 196–200.

Fill, H.-G. (2017). SeMFIS: A flexible engineering platform for semantic annotations of conceptual models. *Semantic Web*, 8(5):747–763.

Fraser, A. M. (2008). *Hidden Markov models and dynamical systems*. Philadelphia: SIAM.

Kumar, A., Chinnam, R.B., & Tseng, F. (2018). An HMM and polynomial regression based approach for remaining useful life and health state estimation of cutting tools. *Computers & Industrial Engineering*, 128:1008–1014.

Li, Z., Fang, H., Huang, M., Wei, Y., & Zhang, L. (2018). Data-driven bearing fault identification using improved hidden Markov model and self-organizing map. *Computers & Industrial Engineering*, 116:37–46.

Liao, T. W., Hua, G., Qu, J., & Blau, P. J. (2006). Grinding Wheel Condition Monitoring with Hidden Markov Model-based Clustering Methods. *Machining Science & Technology: An International Journal*, 10(4):511–538.

Liao, W., Li, D., & Cui, S. (2016). A heuristic optimization algorithm for HMM based on SA and EM in machinery diagnosis. *Journal of Intelligent Manufacturing*, 29(8):1845–1857.

Mba, C. U., Makis, V., Marchesiello, S., Fasana, A., & Garibaldi, L. (2018). Condition monitoring and state classification of gearboxes using stochastic resonance and hidden Markov models. *Measurement*, 126:76–95.

Nguyen, N. (2017). An Analysis and Implementation of the Hidden Markov Model to Technology Stock Prediction. *Risks*, 5(4):62:1–62:18.

Oliveira, W., Ambrósio, L. M., Braga, R., Ströele, V., David, J. M., & Campos, F. (2017). A Framework for Provenance Analysis and Visualization. *Procedia Computer Science*, 108:1592–1601.

Padovano, A., Longo, F., Nicoletti, L., & Mirabelli, G. (2018). A Digital Twin based Service Oriented Application for a 4.0 Knowledge Navigation in the Smart Factory. *IFAC-PapersOnLine*, 51(11):631–636.

Qi, Q., Tao, F., Zuo, Y., & Zhao, D. (2018). Digital Twin Service towards Smart Manufacturing. *Procedia CIRP*, 72:237–242.

Ramos, L. (2015). Semantic Web for manufacturing, trends and open issues: Toward a state of the art. *Computers & Industrial Engineering*, 90:444–460.

Talkhestani, B. A., Jazdi, N., Schloegl, W., & Weyrich, M. (2018). Consistency check to synchronize the Digital Twin of manufacturing automation based on anchor points. *Procedia CIRP*, 72:159–164.

Ullah, AMM S. (2019). Modeling and simulation of complex manufacturing phenomena using sensor signals from the perspective of Industry 4.0. *Advanced Engineering Informatics*, 39(1):1–13.

Ullah, A. M. M. S. (2017). Surface Roughness Modeling Using Q-Sequence. *Mathematical and Computational Applications*, 22(2):33:1–33:12

Visser, I. (2011). Seven things to remember about hidden Markov models: A tutorial on Markovian models for time series. *Journal of Mathematical Psychology*, 55(6):403–415.

Wu, D., Terpenny, J., & Schaefer, D. (2016). Digital design and manufacturing on the cloud: A review of software and services. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 31(1):104–118.

Xie, F.-Y., Hu, Y.-M., Wu, B., & Wang, Y. (2016). A generalized hidden Markov model and its applications in recognition of cutting states. *International Journal of Precision Engineering and Manufacturing*, 17(11):1471–1482.

Zhang, S., Zhang, Y., & Zhu, J. (2018). Residual life prediction based on dynamic weighted Markov model and particle filtering. *Journal of Intelligent Manufacturing*, 29(4):753–761.