# Robust Dynamic Latent Variable Model for Dynamic Process monitoring with Missing Data in Cyber-Physical Systems

Le Zhou, *Student Membership*, Lixinqian Yu, *Membership*, Beiping Hou, Hongbo Zheng and Zheng-Guang Wu, *Membership*

***Abstract*—Although remarkable studies on dynamic process modeling and monitoring in cyber-physical systems have been conducted, there are still several limitations to these approaches, rendering them unsuitable for practical applications. Firstly, the common dynamic models are built based on complete data, which means that their modeling performance usually deteriorates when there are missing measurements. Secondly, practical data often exhibits more complex characteristics, such as non-stationary and non-Gaussian noises. Therefore, a robust dynamic latent variable model is proposed to address the challenges of dynamic process modeling and monitoring in complex measurement environments with missing values. The proposed method effectively handles non-Gaussian noises and recursively estimates missing values, thus enhancing the monitoring performance within the dynamic latent variable modeling framework. Finally, the feasibility and superiority of the proposed method are evaluated through a numerical example and a real wastewater treatment case, demonstrating its effectiveness and practicality in real-world scenarios.**

***Index Terms*—EM algorithm, Missing values, Process monitoring, Robust dynamic latent variable models.**

## I. INTRODUCTION

As industrial facilities and sensor technologies are continuously upgrading in the cyber-physical systems (CPS), the reliability and security of industrial processes have gained increasing significance. Consequently, the process monitoring method has been extensively developed by the deployment of artificial intelligence techniques in the field of process control over the last few decades. [1] Among them, data-based multivariate statistical process monitoring (MSPM) offers an easy-to-implement architecture in CPS without precise empirical knowledge and physical models [2]–[4]. Based on these models, a low-dimensional variable space is built to extract the essential features of the dataset in the traditional MSPM such as principal component analysis (PCA), partial least squares (PLS), and so forth [5][4-8]. Besides, the validity of these models and their extensions have also been proven in fault detection, isolation and root cause diagnosis [9].

However, traditional modeling methodologies in CPS focused too much attention on the cross correlations of the data. Actually, the dynamic relationship, which is also termed as auto-correlation, is another essential characteristic of the process data. To resolve dynamic modeling, Ku et al. [4] extracted auto-correlations by constructing an augmented matrix based on PCA, which was called dynamic PCA (DPCA) model. Furthermore, an indirect DPCA based on a consistent DPCA algorithm was introduced by Li and Qin [10]. Due to the ability to model the relationship between two datasets, canonical variate analysis (CVA) and PLS were also able to predict the future variables in the data and were used for dynamic modeling, respectively [11-12].

In spite of the proven ability of the above models to extract auto-correlations, they leave the cross correlations unmodeled. To incorporate both the static and dynamic relationship, Wen et al. [13] proposed a new probabilistic framework named data-based linear gaussian state-space model (LGSSM), which was also suitable to deal with datasets contaminated by stochastic noises. Besides, a novel method called dynamic latent-variable (DLV) modeling has been proposed by Li et al [14]. The method applied the structured DPCA algorithm and a vector autoregressive (AR) model to build DLVs, as well as performing PCA to illustrate cross correlations. Furthermore, Zhou et al. [15] designed an autoregressive DLV (ARDLV) model, which built a low-dimensional subspace for DLVs and the developed structure can concurrently extract the auto-correlations and cross correlations. Hence, it is more appropriate for dynamic process monitoring.

The above methods are usually constructed based on the complete dataset. In the practical industries, however, the above hypothesis cannot be entirely satisfied due to inconsistent sampling rates or stochastic sensor failures, which actually gives rise to data contaminating with missing values and outliers [16-17]. For solving the missing values issues, Chen & Sun developed a probabilistic contribution analysis approach, which integrates PPCA and mixture PPCA models to identify the contribution of fault variables [18]. Fan et al. applied kernel

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methods to not only identify faults but also account for missing data, thereby improving monitoring performance [19]. Jiang et al. proposed a neighborhood variational Bayesian multivariate analysis method that handled missing data in distributed process monitoring [20]. Luo et al. developed a two-step cellwise outlier filters and generalized Rock S-estimators (COF-GRE) model for the simultaneous identification and substitution of outliers and missing values [21]. Additionally, Dai et al. [22] introduced the variational Bayesian student's-t mixture model (VBSMM) method, along with a novel control statistic called EVD, to propose a closed-form imputation methodology for low-quality data that included missing values. Nonetheless, it is noticed that these existing missing-data based models are still constructed under the assumption that the data are static correlated. However, they leave the autocorrelations unmodeled and simultaneously neglect non-Gaussian noises.

The above research has explored various efficient modeling strategies for handling incomplete measurements. However, non-Gaussian noise is frequently encountered in practical scenarios, as it offers a more precise depiction of many practical environments compared to Gaussian noise. In order to handle non-Gaussian noise, some alternate modeling techniques are used. Certainly, the formulation of an extended independent component analysis (ICA)-based methodology presents an engaging area of research. This includes the integration of ICA and Principal Component Analysis (PCA) [23], as well as a hybrid ICA-PCA with the relevant vector machine [24]. These methodologies are proficient in discerning non-Gaussian and mutually independent variables within the structure of PCA. Alternatively, Huang & Yan employed the VDSPM method to segregate the non-Gaussian subspace from the Gaussian distribution, subsequently applying ICA and PCA to these distinct areas respectively [25]. Furthermore, Zhu et al. proposed the probabilistic independent component analysis (PICA). By applying student's-t distribution, it adeptly captures the characteristics of both Gaussian and non-Gaussian measurements [26].

Additionally, recent studies have turned their attention to addressing dynamic non-Gaussian issues. Rashid introduced an ICA model incorporating multidimensional mutual information, which enhances both accuracy and efficiency when monitoring dynamic non-Gaussian processes [27]. Li et al. employed a mixture of DICA and DPCA models in sequence, effectively capturing both Gaussian and non-Gaussian dynamics within process data [28]. In practical application, however, these dynamic ICA-based models often rely on fragmented and incomplete information extracted from datasets containing missing values. To tackle these challenges, this paper proposes a novel robust dynamic latent variable (RDLV) model. RDLV utilizes the ICA model on incomplete datasets to estimate missing values and to extract non-Gaussian noise. Following this, the residuals are processed through a recursive autoregressive dynamic latent variable model. This iterative approach to re-estimating missing values enhances performance in terms of process monitoring and fault detection.

The layout of this paper is organized as follows. Section II provides a brief review of the existing ARDLV model. Section III presents a thorough exploration of the Robust Dynamic Latent Variable Model. The corresponding fault detection strategies are then developed in Section IV. Section V showcases a numerical example along with a real wastewater treatment process to assess the efficacy of the proposed method in process modeling and monitoring. Finally, some conclusions are made.

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1) Regular Papers and Special Section papers - Four to eight pages, including authors' bios and photos.
2) Letters - One to three pages. Authors' bios and photos must not be included.

## II. Autoregressive Dynamic Latent Variable Model

In this section, ARDLV model is concisely reviewed, which severs as the preliminary of this article. At sampling time k, suppose

## III. Submission of a new manuscript for review

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Authors should consider the following points before submitting a new paper. Otherwise the submission will be automatically rejected.

1) New manuscripts cannot exceed **8 pages** (3 for letters). Only a very limited overlength (1/2 page at most) is tolerated. Note that usually in the review process the reviewers tend to ask for more explanations, also note that the maximum allowed length is 8 pages on initial/first submission, including authors' bios and photos.
2) In order to follow the **single-blind** review process, we ask that all the authors be identifiable within the manuscript (DO include authors' names, their biographies, affiliation, etc.). The articles in this journal are peer reviewed in accordance with the requirements set forth in the IEEE Publication Services and Products Board Operations Manual (https://pspb.ieee.org/images/files/files/opsmanual.pdf). Each published article was reviewed by a minimum of two independent reviewers using a single-blind peer review process, where the identities of the reviewers are not known to the authors, but the reviewers know the identities of the authors. Articles will be screened for plagiarism before acceptance.
3) If a significant portion of your manuscript was already published at a conference you must use our **"Post Conference Papers" template**. The manuscript must include the previous work in the references section.
4) TIE policy **doesn't consider surveys**, state of the art papers or project reports. Only Guest Editors of a special section (or submissions allowed by the Editorial Board) are invited to submit such kind of manuscript. Our typical papers propose new methods and demonstrate their effectiveness through experimental results in combination with simulation results.
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13) Your paper should describe very clearly your accomplishments so other people can understand what your **original contribution** is and use it. Notice that usually your technical accomplishments will be evaluated based on the number of citations but not based on the number of papers published.
14) **Write clearly your manuscript**. Try to keep your manuscript on the proper level from one section to another. It should be easy to understand by well-qualified professionals, but at the same time please avoid describing well-known facts (use proper references instead). Often manuscripts receive negative reviews because reviewers are not able to understand the manuscript and this is authors' (not reviewers') fault. Notice, that if reviewers have difficulties, then other readers will face the same problem and there is no reason to publish the manuscript.

## IV. Submission of a Revised Manuscript for Review

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The checklist above "TIE checklist for manuscript submissions" also applies to the revised stage.

In the revision flow, the reviewers tend to ask for more explanations, also note that the maximum allowed length is

8 pages and exceptionally up to 10 pages may be authorized (paying an overlength fee). Note that the page count includes the authors' bios and photos

In the resubmission flow, please include a cover letter that mentions this paper number and describes the major changes to the manuscript. In particular, please summarize the new results that have been added. This should be accompanied by a point by point explanation of 1) how the previous comments from the reviewers were addressed and 2) how new results added to the paper make it stronger and increase the research contribution. The response to reviewers should be uploaded as a "supplementary file," in addition to being uploaded as a cover letter so that all reviewers will have access to the file. Lastly, please make sure to highlight the changes in the paper (or at least use a different font color). If the changes are too much, highlight the major additions to the paper. Please do not submit a paper with track changes, as track changes make the paper difficult for reviewers to read.

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Upon acceptance, you will receive an email with specific instructions regarding the submission of your final files. To avoid any delays in publication, please be sure to follow these instructions. Final submissions should include source files of your accepted manuscript, high quality graphic files, and a formatted PDF file. If you have any questions regarding the final submission process, please contact the administrative contact for the journal.

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## VI. Guidelines for Manuscript Preparation

A general IEEE style guide is available at https://ieeeauthorcenter.ieee.org/.

### A. Abbreviations and Acronyms

Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract. Abbreviations such as IEEE, SI, ac, and dc do not have to be defined. Abbreviations that incorporate periods should not have spaces: write "C.N.R.S.," not "C. N. R. S." Do not use abbreviations in the title unless they are unavoidable (for example, "IEEE" in the title of this article).

### B. Other Recommendations

Use one space after periods and colons. Hyphenate complex modifiers: "zero-field-cooled magnetization." Avoid dangling participles, such as, "Using (1), the potential was calculated." [It is not clear who or what used (1).] Write instead, "The potential was calculated by using (1)," or "Using (1), we calculated the potential."

Use a zero before decimal points: "0.25," not ".25." Use "cm3," not "cc." Indicate sample dimensions as "0.1 cm x 0.2 cm," not "0.1 x 0.2 cm2." The abbreviation for "seconds" is "s," not "sec." Use "Wb/m2" or "webers per square meter," not "webers/m2." When expressing a range of values, write "7 to 9" or "7-9," not "7 9.".

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If you are using Word, use either the Microsoft Equation Editor or the MathType add-on (http://www.mathtype.com) for equations in your paper (Insert — Object — Create New — Microsoft Equation or MathType Equation). "Float over text" should not be selected.

### A. Equations

Number equations consecutively with equation numbers in parentheses flush with the right margin, as in (1). First use the equation editor to create the equation. Then select the "Equation" markup style. Press the tab key and write the equation number in parentheses. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

$$\int_0^{r_2} F(r,\varphi) dr\ d\varphi = [\sigma r_2/(2\mu_0)] \int_0^{\infty} exp(-\lambda|z_j - z_i|)\lambda^{-1} J_1(\lambda r_2) J_0(\lambda r_i) d\lambda. \quad (1)$$

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (T might refer to temperature, but T is the unit tesla). Refer to "(1)," not "Eq. (1)" or "equation (1)," except at the beginning of a sentence: "Equation (1) is ..." .

## VIII. Units

Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). This applies to papers in data storage. For example, write "15 Gb/cm2 (100 Gb/in2)." An exception is when English units are used as identifiers in trade, such as "3ï¿½-in disk drive." Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as µ0H. Use the center dot to separate compound units, e.g., "Aï¿½m2."

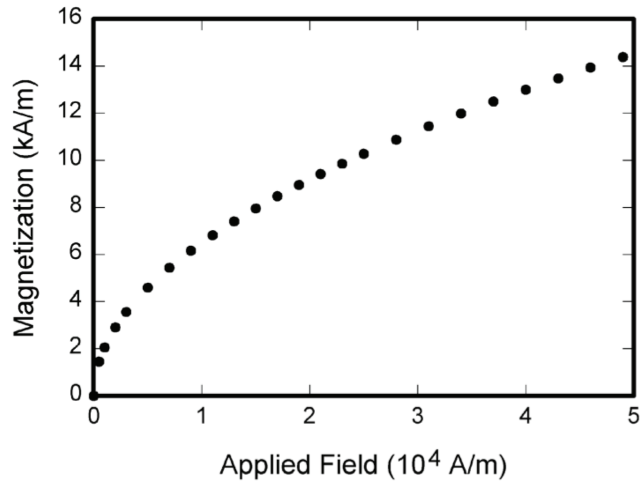


Fig. 1. Magnetization as a function of applied field. Note that "Fig." is abbreviated. There is a period after the figure number, followed by two spaces. It is good practice to explain the significance of the figure in the caption.

## IX. Guidelines for Graphics Preparation and Submission

### A. Types of Graphics

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray.

Such figures may include photographs, illustrations, multicolor graphs, and flowcharts.

Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray. Only black and white.

Head and shoulders shots of authors which appear at the end of our papers. Data charts which are typically black and white, but sometimes include color.

### B. Multipart figures

Figures compiled of more than one sub-figure presented side-by-side, or stacked. If a multipart figure is made up of multiple figure types (one part is lineart, and another is grayscale or color) the figure should meet the stricter guidelines.

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Format and save your graphics using a suitable graphics processing program that will allow you to create the images as PostScript (PS), Encapsulated PostScript (.EPS), Tagged Image File Format (.TIFF), Portable Document Format (.PDF), or Portable Network Graphics (.PNG) sizes them, and adjusts the resolution settings. If you created your source files in one of the following programs you will be able to submit the graphics without converting to a PS, EPS, TIFF, PDF, or PNG file: Microsoft Word, Microsoft PowerPoint, or Microsoft Excel. Though it is not required, it is recommended that these files be saved in PDF format rather than DOC, XLS, or PPT. Doing so will protect your figures from common font and

TABLE I
UNITS FOR MAGNETIC PROPERTIES

| Symbol | Quantity | Conversion from Gaussian and CGS EMU to $SI^a$ |
|---|---|---|
| $\Phi$ | magnetic flux | $1Mx \to 10^8 Wb = 10^8 V \cdot s$ |
| $B$ | magnetic flux density, magnetic induction | $1G \to 10^4 T = 10^4 Wb/m^2$ |
| $H$ | magnetic field strength | $1Oe \to 10^3/(4\pi) A/m$ |
| $m$ | magnetic moment | $1erg/G = 1emu \to 10^3 A \cdot m^2 = 10^3 J/T$ |
| $M$ | magnetization | $1erg/(G \cdot cm^3) = 1emu/cm^3 \to 10^3 A/m$ |
| $4\pi M$ | magnetization | $1G \to 10^3/(4\pi) A/m$ |
| $\sigma$ | specific magnetization | $1erg/(G \cdot g) = 1emu/g \to 1A \cdot m^2/kg$ |
| $j$ | magnetic dipole moment | $1erg/G = 1emu \to 4\pi \times 10^{10} Wb \cdot m$ |
| $J$ | magnetic polarization | $1erg/(G \cdot cm^3) = 1emu/cm^3 \to 4\pi \times 10^4 T$ |
| $\chi$ $\kappa$ | susceptibility | $1 \to 4\pi$ |
| $\chi$ | mass susceptibility | $1cm^3/g \to 4\pi \times 10^3 m^3/kg$ |
| $\mu$ | permeability | $1 \to 4\pi \times 10^7 H/m = 4\pi \times 10^7 Wb/(A \cdot m)$ |
| $\mu_r$ | relative permeability | $\mu \to \mu_r$ |
| $\omega, W$ | energy density | $1erg/cm^3 \to 10^1 J/m^3$ |
| $N, D$ | demagnetizing factor | $1 \to 1/(4\pi)$ |

arrow stroke issues that occur when working on the files across multiple platforms. When submitting your final paper, your graphics should all be submitted individually in one of these formats along with the manuscript.

### D. Sizing of Graphics

Most charts, graphs, and tables are one column wide (3.5 inches / 88 millimeters / 21 picas) or page wide (7.16 inches / 181 millimeters / 43 picas). The maximum depth a graphic can be is 8.5 inches (216 millimeters / 54 picas). When choosing the depth of a graphic, please allow space for a caption. Figures can be sized between column and page widths if the author chooses, however it is recommended that figures are not sized less than column width unless when necessary.

There is currently one publication with column measurements that don't coincide with those listed above. PROCEEDINGS OF THE IEEE has a column measurement of 3.25 inches (82.5 millimeters / 19.5 picas).

The final printed size of author photographs is exactly 1 inch wide by 1.25 inches tall (25.4 millimeters x 31.75 millimeters / 6 picas x 7.5 picas). Author photos printed in editorials measure 1.59 inches wide by 2 inches tall (40 millimeters x 50 millimeters / 9.5 picas x 12 picas).

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While IEEE does accept, and even recommends that authors submit artwork in vector format, it is our policy is to rasterize all figures for publication. This is done in order to preserve the figures' integrity across multiple computer platforms.

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The term color space refers to the entire sum of colors that can be represented within the said medium. For our purposes, the three main color spaces are Grayscale, RGB (red/green/blue) and CMYK (cyan/magenta/yellow/black). RGB is generally used with on-screen graphics, whereas CMYK is used for printing purposes.

All color figures should be generated in RGB or CMYK color space. Grayscale images should be submitted in Grayscale color space. Line art may be provided in grayscale OR bitmap colorspace. Note that "bitmap colorspace" and "bitmap file format" are not the same thing. When bitmap color space is selected, .TIF/.TIFF is the recommended file format.

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When preparing your graphics IEEE suggests that you use of one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, and Symbol. If you are supplying EPS, PS, or PDF files all fonts must be embedded. Some fonts may only be native to your operating system; without the fonts embedded, parts of the graphic may be distorted or missing.

A safe option when finalizing your figures is to strip out the fonts before you save the files, creating "outline" type. This converts fonts to artwork what will appear uniformly on any screen.

### I. Using Labels Within Figures

1) Figure Axis labels
   Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the label "Magnetization," or "Magnetization M," not just "M." Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write "Magnetization (A/m)" or "Magnetization (A m1)," not just "A/m." Do not label axes with a ratio of quantities and units. For example, write "Temperature (K)," not "Temperature/K.". Multipliers can be especially confusing. Write "Magnetization (kA/m)" or "Magnetization (103 A/m)." Do not write "Magnetization (A/m) x 1000" because the reader would not know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 10 point type.
2) Subfigure Labels in Multipart Figures and Tables
   Multipart figures should be combined and labeled before final submission. Labels should appear centered below each subfigure in 8 point Times New Roman font in the format of (a) (b) (c).

### J. Referencing a Figure or Table Within Your Paper

When referencing your figures and tables within your paper, use the abbreviation "Fig." even at the beginning of a sentence. Do not abbreviate "Table." Tables should be numbered with Roman Numerals.

### K. Checking Your Figures: The IEEE Graphics Checker

The IEEE Graphics Checker Tool enables authors to pre-screen their graphics for compliance with IEEE Transactions and Journals standards before submission. The online tool, located at http://graphicsqc.ieee.org/, allows authors to upload their graphics in order to check that each file is the correct file format, resolution, size and colorspace; that no fonts are missing or corrupt; that figures are not compiled in layers or have transparency, and that they are named according to the IEEE Transactions and Journals naming convention. At the end of this automated process, authors are provided with a detailed report on each graphic within the web applet, as well as by email.

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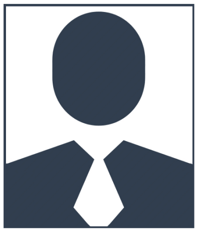

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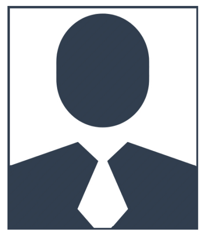

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