Iterative Learning Control of a Pneumatically Driven Robot Joint

1st Rainer Nitsche
Robotics System Design
Festo SE & Co. KG
Esslingen, Germany
rainer.nitsche@festo.com

2nd Timo Heubach
Robotics System Design
Festo SE & Co. KG
Esslingen, Germany
timo.heubach@festo.com

***Abstract*—In this contribution the concept of *Iterative Learning Control (ILC)* is introduced and applied to a pneumatically driven joint build-in a pneumatic cobot. Iterative Learning Control is highly suitable to repeatable control tasks as they appear typically in robot applications [6].**

***Index Terms*—model-based control, robot control**

I. Introduction

Robot control tasks often follows a repeating trajectory. For this kind of application the concept of learning from the error of the previous control run lies on the hand. That's why in the field of robot control the concept of ILC is often used [1]. In [2] the concept for

II. Control Task

As a drafted version the paper of Steinboeck can be used [7]

A. Model of the Pneumatic Robot Joint

In this research a single joint (cf. Fig. 2) of a pneumatic robot (cf. Fig. 1) is considered. In this pneumatically driven revolute joint, the two pressure chambers are separated by a swivel wing of area A_{eff} and an effective radius R_{eff}, which is semi-rotatable to $\pm 135°$. The pressure difference between the two chambers 1 and 2 of the joint generates a driving torque

$$\tau(p_1, p_2) = A_{\text{eff}}\ R_{\text{eff}}\ (p_1 - P_2). \tag{1}$$

The pressure in each chamber is set individually by a massflow $\dot{m}_{1,2}$ into or out of the chamber with a pneumatic valve, not considered in detail here. A more detailed overview of the pneumatic model can be found in [3].

The governing equations of the rotary joint model are:

$$\ddot{q} = \frac{A_{\text{eff}} R_{\text{eff}} (p_1 - p_2)}{J}, \tag{2a}$$

$$\dot{p}_2 = \frac{nRT}{V_{\text{dead},2} + A_{\text{eff}}\ R_{\text{eff}}\ (\ |q_{\max} - q)} \dot{m}_2 - \frac{np_2 A_{\text{eff}} R_{\text{eff}} \dot{q}}{V_{\text{dead},2} + A_{\text{eff}}\ R_{\text{eff}}\ (\ |q_{\max} - q)}, \tag{2b}$$

$$\dot{p}_1 = \frac{nRT}{V_{\text{dead},1} + A_{\text{eff}} R_{\text{eff}} (\ |q_{\min} + q)} \dot{m}_1 + \frac{nP_1 A_{\text{eff}} R_{\text{eff}} \dot{q}}{V_{\text{dead},1} + A_{\text{eff}} R_{\text{eff}} (\ |q_{\min} + q)}, \tag{2c}$$

where the A_{eff}
See also [5], and [4].

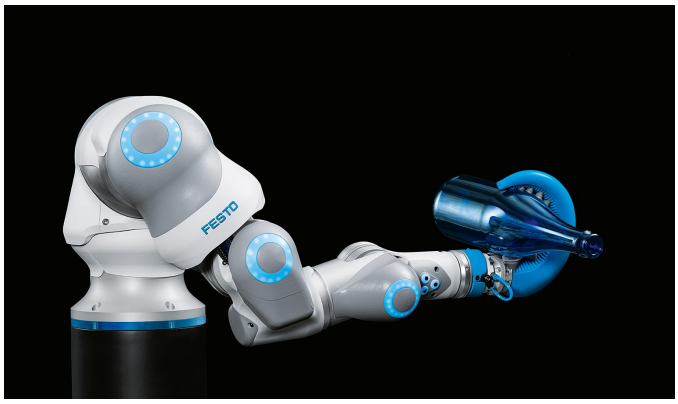

Fig. 1. Pneumatic Cobot from Festo (2020)

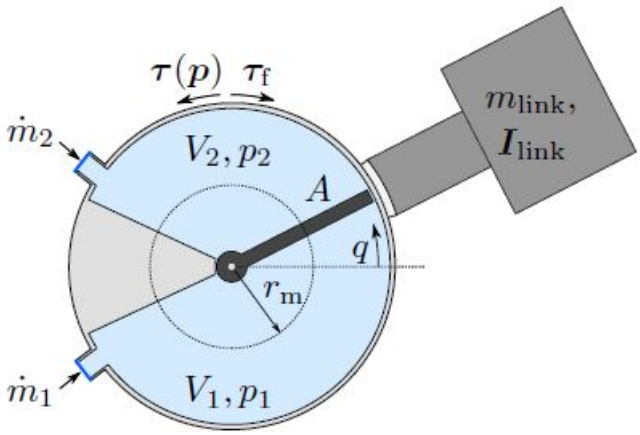

Fig. 2. Schematics of a pneumatic rotary joint [5].

III. Controller Design

Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections III-A–III-E below for more information on proofreading, spelling and grammar.

Keep your text and graphic files separate until after the text has been formatted and styled. Do not number text heads—LaTeX will do that for you.

A. Flatness-based Approach

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, ac, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

B. Iterative Learning Control

Rather following the approach from [2].

- Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as "3.5-inch 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 that you use in an equation.
- Do not mix complete spellings and abbreviations of units: "Wb/m^2" or "webers per square meter", not "webers/m^2". Spell out units when they appear in text: ". . . a few henries", not ". . . a few H".
- Use a zero before decimal points: "0.25", not ".25". Use "cm^3", not "cc".)

C. Equations

Number equations consecutively. To make your equations more compact, you may use the solidus (/), the exp function, or appropriate exponents. Italicize Roman symbols for quantities and variables, but not Greek symbols. Use a long dash rather than a hyphen for a minus sign. Punctuate equations with commas or periods when they are part of a sentence, as in:

$$a + b = \gamma \tag{3}$$

Be sure that the symbols in your equation have been defined before or immediately following the equation. Use "(3)", not "Eq. (3)" or "equation (3)", except at the beginning of a sentence: "Equation (3) is . . ."

D. LaTeX-Specific Advice

Please use "soft" (e.g., `\eqref{Eq}`) cross references instead of "hard" references (e.g., `(1)`). That will make it possible to combine sections, add equations, or change the order of figures or citations without having to go through the file line by line.

Please don't use the `{eqnarray}` equation environment. Use `{align}` or `{IEEEeqnarray}` instead. The `{eqnarray}` environment leaves unsightly spaces around relation symbols.

Please note that the `{subequations}` environment in LaTeX will increment the main equation counter even when there are no equation numbers displayed. If you forget that, you might write an article in which the equation numbers skip from (17) to (20), causing the copy editors to wonder if you've discovered a new method of counting.

BibTeX does not work by magic. It doesn't get the bibliographic data from thin air but from .bib files. If you use BibTeX to produce a bibliography you must send the .bib files.

LaTeX can't read your mind. If you assign the same label to a subsubsection and a table, you might find that Table I has been cross referenced as Table IV-B3.

LaTeX does not have precognitive abilities. If you put a `\label` command before the command that updates the counter it's supposed to be using, the label will pick up the last counter to be cross referenced instead. In particular, a `\label` command should not go before the caption of a figure or a table.

Do not use `\nonumber` inside the `{array}` environment. It will not stop equation numbers inside `{array}` (there won't be any anyway) and it might stop a wanted equation number in the surrounding equation.

E. Some Common Mistakes

- The word "data" is plural, not singular.
- The subscript for the permeability of vacuum μ_0, and other common scientific constants, is zero with subscript formatting, not a lowercase letter "o".
- In American English, commas, semicolons, periods, question and exclamation marks are located within quotation marks only when a complete thought or name is cited, such as a title or full quotation. When quotation marks are used, instead of a bold or italic typeface, to highlight a word or phrase, punctuation should appear outside of the quotation marks. A parenthetical phrase or statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.)
- A graph within a graph is an "inset", not an "insert". The word alternatively is preferred to the word "alternately" (unless you really mean something that alternates).
- Do not use the word "essentially" to mean "approximately" or "effectively".
- In your paper title, if the words "that uses" can accurately replace the word "using", capitalize the "u"; if not, keep using lower-cased.
- Be aware of the different meanings of the homophones "affect" and "effect", "complement" and "compliment", "discreet" and "discrete", "principal" and "principle".
- Do not confuse "imply" and "infer".
- The prefix "non" is not a word; it should be joined to the word it modifies, usually without a hyphen.
- There is no period after the "et" in the Latin abbreviation "et al.".
- The abbreviation "i.e." means "that is", and the abbreviation "e.g." means "for example".

An excellent style manual for science writers is [2].

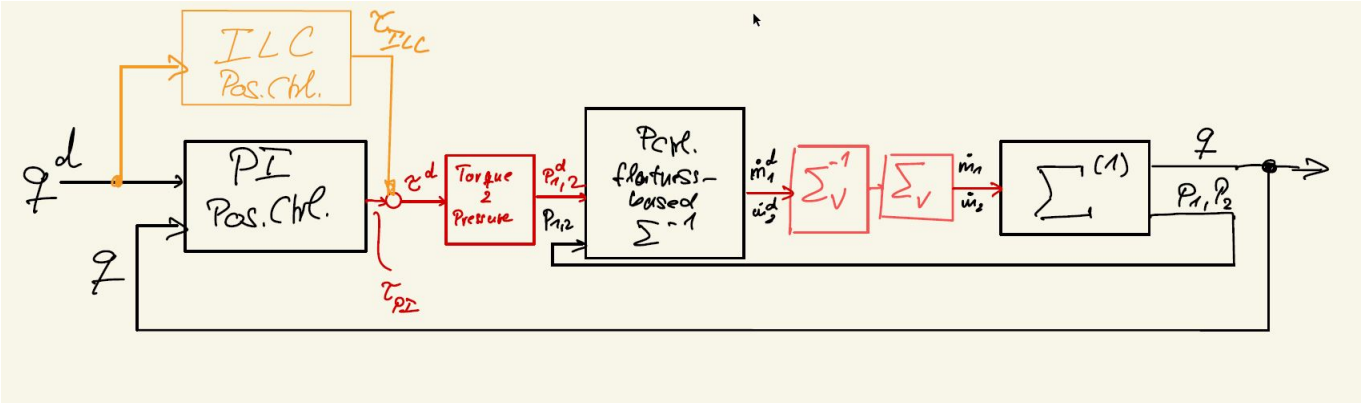

Fig. 3. Control Structure

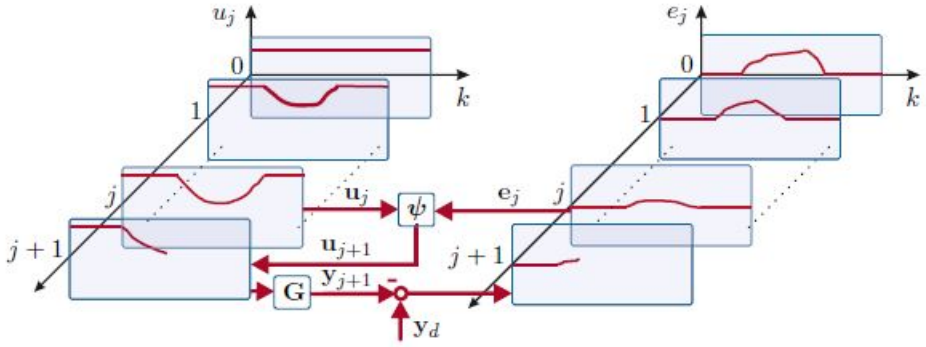

Fig. 4. Illustration of the ILC concept [2]

F. Authors and Affiliations

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G. Identify the Headings

Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads.

Component heads identify the different components of your paper and are not topically subordinate to each other. Examples include Acknowledgments and References and, for these, the correct style to use is "Heading 5". Use "figure caption" for your Figure captions, and "table head" for your table title. Run-in heads, such as "Abstract", will require you to apply a style (in this case, italic) in addition to the style provided by the drop down menu to differentiate the head from the text.

Text heads organize the topics on a relational, hierarchical basis. For example, the paper title is the primary text head because all subsequent material relates and elaborates on this one topic. If there are two or more sub-topics, the next level head (uppercase Roman numerals) should be used and, conversely, if there are not at least two sub-topics, then no subheads should be introduced.

H. Figures and Tables

a) Positioning Figures and Tables: Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation "Fig. **??**", even at the beginning of a sentence.

TABLE I
TABLE TYPE STYLES

Table Head	**Table Column Head**		
	Table column subhead	***Subhead***	***Subhead***
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[a]Sample of a Table footnote.

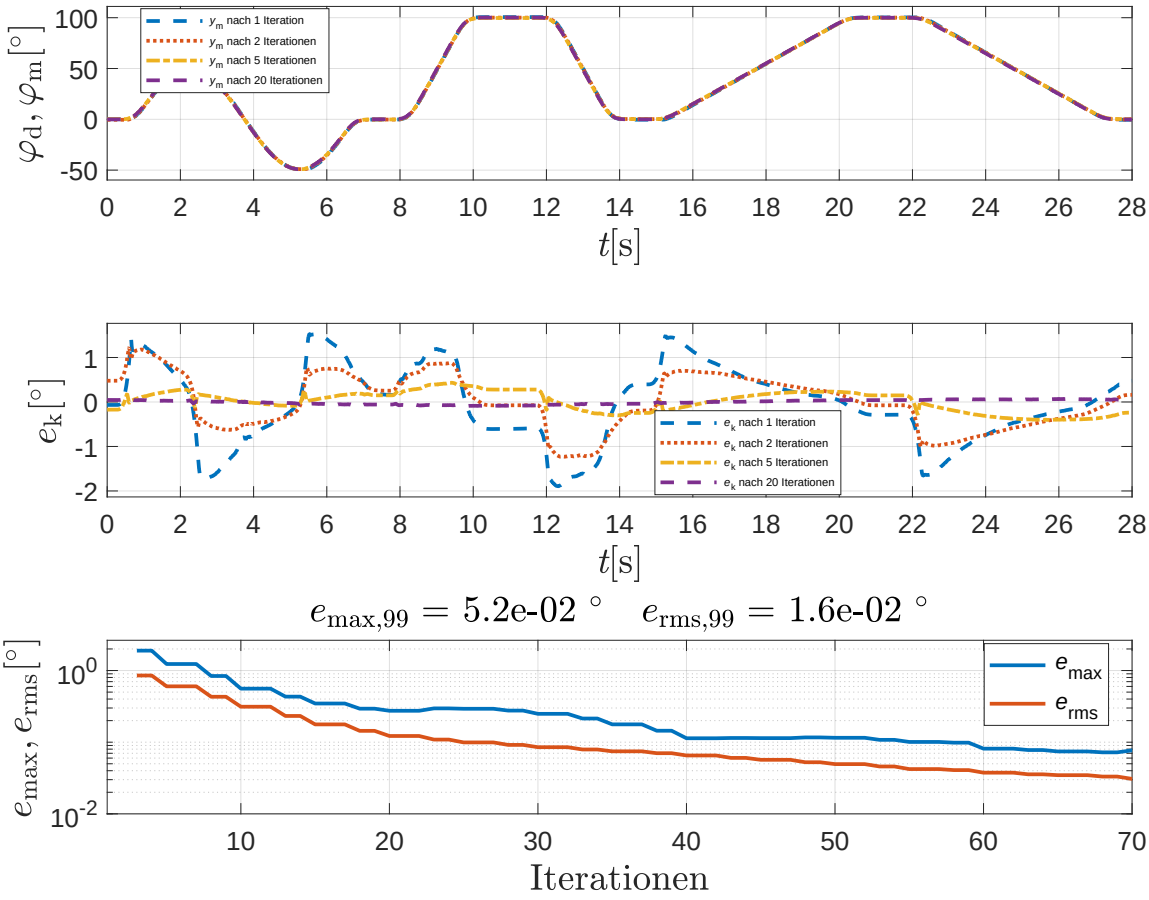

Fig. 5. Measurement resutls for a robot joint

Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity "Magnetization", or "Magnetization, M", not just "M". If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write "Magnetization (A/m)" or "Magnetization {A[m(1)]}", not just "A/m". Do not label axes with a ratio of quantities and units. For example, write "Temperature (K)", not "Temperature/K".

ACKNOWLEDGMENT

The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression "one of us (R. B. G.) thanks ...". Instead, try "R. B. G. thanks...". Put sponsor acknowledgments in the unnumbered footnote on the first page.

REFERENCES

REFERENCES

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