Industrial Stack Emissions Monitoring: Enhancing Pollution Assessment with Multirotor Drone Technology

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[[1]](#footnote-1)

***Abstract*—This research focuses on the conceptual design of a stack emissions monitoring drone, addressing the critical issue of monitoring industrial stacks to control air pollution. The inherent risks associated with monitoring tall chimneys, particularly in refineries, pose threats to human lives and health. By employing an aerial robotic system, these risks are eliminated while simultaneously reducing time and operational costs. Through rigorous demand and mission analysis, the design process is structured into five stages: 1. Selection of an avian-inspired manipulator and sampling probe, 2. Configuration layout, 3. Selection of an appropriate monitoring sensor, 4. Iterative weight estimation and propulsion selection, and 5. Identification of subsystems and key components. To optimize the manipulator's installation, an optimization process is employed. Design decisions are guided by quantified criteria, ensuring a systematic and objective approach. The presented novel design sketch exemplifies the potential of the proposed concept, emphasizing the importance of adopting a systematic design view in effectively addressing the critical issue of stack emissions monitoring. (Needs to be revised and finalized at the end)**

***Index Terms*—Air Pollution Control, Aerial Emissions Monitoring, Manipulator Design Optimization , Multirotor**

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# I. INTRODUCTION

I

ndustrial stack emissions monitoring is one of pivotal aspect of environmental protection, playing a crucial role in mitigating the adverse effects of air pollution on human health and the ecosystem. The escalating consumption of fossil fuels, driven by economic growth, population expansion, and industrialization, has led to a significant increase in emissions of harmful pollutants such as carbon dioxide (CO₂), sulfur dioxide (SO₂), nitrogen oxides (NOₓ), and particulate matter (PM2.5 and PM10) [1]. These pollutants not only contribute to global warming but also exacerbate respiratory diseases and other health issues, underscoring the urgent need for effective monitoring and control mechanisms.

The advent of unmanned aerial vehicles (UAVs), commonly known as drones, has revolutionized various industries, including environmental monitoring. UAVs offer a versatile and cost-effective solution for tasks that are hazardous, time-consuming, or logistically challenging. Their ability to operate in confined spaces, access hard-to-reach areas, and collect high-resolution data in real-time has made them indispensable tools in fields ranging from agriculture to disaster response [2] [3].

Current methods for industrial stack emissions monitoring primarily rely on ground-based sensors, manual inspections, and satellite imaging. Ground-based sensors provide localized data but are limited in their spatial coverage and flexibility. According to the World Health Organization, 99% of the global population breathes air that exceeds guideline limits and contains high levels of pollutants (Ref 6). Manual inspections, while detailed, are labor-intensive, time-consuming, and pose significant risks to human operators, particularly in hazardous environments such as refineries and chemical plants (Ref 1). Satellite imaging offers a broader perspective but is often limited by cloud cover, resolution, and the inability to provide real-time data. These limitations highlight the need for a more comprehensive and automated approach to emissions monitoring.

The automation of industrial stack emissions monitoring using UAVs addresses many of the shortcomings of traditional methods. UAVs can be equipped with a variety of sensors to detect and quantify pollutants in real-time, providing continuous monitoring and immediate feedback. This not only enhances the accuracy and reliability of emissions data but also reduces the operational costs and risks associated with manual inspections. Moreover, UAVs can be deployed rapidly to respond to sudden changes in emissions, such as those resulting from equipment failures or operational anomalies (Ref 3).

The benefits of UAVs in industrial stack emissions monitoring are multifaceted. Improved safety for workers is a primary advantage, as UAVs eliminate the need for working at heights, in contaminated environments, and in remote or hazardous regions (Ref 3). Reduced cost and time are also significant, as UAV-based inspections do not require scaffolding or support infrastructure, leading to substantial savings (Ref 3). Additionally, UAVs minimize disruption to operations, as they can conduct inspections without shutting down facilities (Ref 3). Better information is another benefit, as UAVs can access hard-to-reach areas to acquire high-resolution images and data (Ref 3). Frequent inspections are feasible due to the low cost and minimal infrastructure requirements, providing more updated data on asset fitness for service (Ref 3).

In this article, we present the conceptual design of a multirotor drone specifically tailored for industrial stack emissions monitoring. The design process is structured into five key stages: selection of an avian-inspired manipulator and sampling probe, configuration layout, sensor selection, iterative weight estimation and propulsion selection, and identification of subsystems and key components. Each stage is guided by quantified criteria to ensure a systematic and objective approach. The proposed design leverages the advantages of UAV technology to enhance pollution assessment, offering a safer, more efficient, and more accurate solution to a critical environmental challenge.

# II. Problem Description & Design Constraints

When you open the template, select “Page Layout” from the “View” menu in the menu bar (View | Page Layout), (these instructions assume Microsoft *Word*. Some versions may have  **Fig. 1.** This is a sample of a figure caption.

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## A. Design Constraints

## B. Standard Flange (stacks inlets for sampling probes)

## D. 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).

# III. Conceptual Design

Use either the Microsoft Equation Editor or the MathType plugin, which can be obtained from <https://store.wiris.com/en/products/mathtype/download>. For help with formatting and placing equations, refer to the *IEEE Editing Math Guide* at <http://journals.ieeeauthorcenter.ieee.org/wp-content/uploads/sites/7/Editing-Mathematics.pdf> and the *IEEE MathType Tutorial for Microsoft Word Users* at <http://journals.ieeeauthorcenter.ieee.org/wp-content/uploads/sites/7/IEEE-Math-Typesetting-Guide-for-MS-Word-Users.pdf>.

TABLE I

This is a Sample of a Table Title



## A. Manipulator Mechanism

## B. Rotors Placement

## C. Weight Estimation & Motor-Prop Selection

## D. Main Components Selection

## E. Design

## A. Equations

Number equations consecutively with equation numbers in parentheses flush with the right margin of the column, 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

*Bp* + *H*2 = 40. (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). When referring to an equation or formula, use simply “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is ... .”

## B. Algorithms

Algorithms should be numbered and include a short title. They are set off from the text with rules above and below the title and after the last line.

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# IV. 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:

* 1. **Color/Grayscale Figures**  
     Figures that are meant to appear in color, or shades of black/gray. Such figures may include photographs,   
     illustrations, multicolor graphs, and flowcharts.
  2. **Line Art Figures**  
     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.
  3. **Tables**  
     Data charts which are typically black and white, but sometimes include color.

## B. Multipart Figures

These are 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 line art, and another is grayscale or color), the figure should meet the stricter guidelines.

## C. File Formats for Graphics

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), JPEG, or Portable Network Graphics (.PNG). These programs can re-size them and adjust 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 strongly 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 arrow stroke issues that occur when working on the files across multiple platforms. When submitting your final files, 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 mm / 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 not be sized less than column width unless when necessary.

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

## E. Resolution

The proper resolution of your figures will depend on the type of figure it is as defined in the “Types of Figures” section. Author photographs, color, and grayscale figures should be at least 300dpi. Line art, including tables should be a minimum of 600dpi.

## F. Vector Art

In order to preserve the figures’ integrity across multiple computer platforms, we accept files in the following formats: .EPS/.PDF/.PS. All fonts must be embedded or text converted to outlines in order to achieve the best-quality results.

## G. Color Space

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/.PNG are the recommended file formats.

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When preparing your graphics, IEEE suggests that you use one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, or 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 which will appear uniformly on any screen.

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   1. Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity “Magnetization” or “Magnetization *M*,” not just “*M*.” Put units in parentheses. Do not label axes only with units. For example, write “Magnetization (A/m)” or “Magnetization (Am−1),” not just “A/m.” Do not label axes with a ratio of quantities and units. For example, write “Temperature (K),” not “Temperature/K.”
   2. Multipliers can be especially confusing. Write “Magnetization (kA/m)” or “Magnetization (103 A/m).” Do not write “Magnetization (A/m) × 1000” because the reader would not know whether the top axis label means 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 Article

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

## K. Submitting Your Graphics

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All IEEE Transactions, Journals, and Letters allow an author to publish color figures on IEEE *Xplore* at no charge, and automatically convert them to grayscale for print versions. In most journals, figures and tables may alternatively be printed in color if an author chooses to do so. Please note that this service comes at an extra expense to the author. If you intend to have print color graphics, you will have the opportunity to indicate this in the Author Gateway and will be contacted by PubOps to confirm the charges.

V. Conclusion

A conclusion section is not required. Although a conclusion may review the main points of the article, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

# Appendix

Appendixes, if needed, appear before the acknowledgment.

# References and Footnotes

## A. References

References need not be cited in text. When they are, they appear on the line, in square brackets, inside the punctuation. Multiple references are each numbered with separate brackets. When citing a section in a book, please give the relevant page numbers. In text, refer simply to the reference number. Do not use “Ref.” or “reference” except at the beginning of a sentence: “Reference [3] shows ... .” Please do not use automatic endnotes in *Word*, rather, type the reference list at the end of the paper using the “References” style.

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Contributions to the Transactions, Journals, and Letters may be submitted electronically on IEEE’s online manuscript submission and peer-review system, ScholarOne Manuscripts. You can get help choosing the correct publication for your manuscript as well as find their corresponding ScholarOne Manuscripts peer review site using the tools listed at <http://www.ieee.org/publications_standards/publications/authors/authors_submission.html> Once you have chosen your publication and navigated to the ScholarOne site, check first to see if you have an existing account. If there is none, please create a new account. After logging in, go to your Author Center and click “Start New Submission.”

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# References

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   Third C. Author is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba 305-0047, Japan (e-mail: author@nrim.go.jp).

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