Low Cost Hardware In The Loop (HIL)

Test Tool

Luis E. Castaneda-Trejo  
The Electrical and Computer Engineering Department  
The University of MichiganDearborn, Michigan USA  
luisct@umich.edu

*Abstract*—Test and Validation teams across several automotive companies use COTS (Commercial Off-the-Shelf) technology for the design and development of Automated Test Equipment (ATE). During System Validation and Verification (V&V) phases, automotive R&D programs budget high costs for professional development tool licenses like Vector CANoe/CANalyzer, Vehicle Spy from Intrepid Control Systems or similar to execute test cases to a vehicle Electronic Control Unit (ECU) under test. While these tools are excellent to design and develop large simulations and tests scenarios, once the design is finished, sometimes they are no longer needed. This project uses a low-cost microcontroller platform that can execute specific test cases to an ECU using CAN protocol commanded by an instruction received by a TCP client.

Keywords—Hardware-in-the-loop, Automated Test, Ethernet, CAN.

# Introduction

Commercial of the Shelf Technology (COTS) offer several solutions out of the box for automotive communications. Companies like Vector Informatik or Intrepid Control Systems have specialized hardware and software tools to simulate complete Electronic Control Units (ECUs). Some of these commercial tools have become a standard in the automotive industry.

In R&D disciplines, most of System Validation and Verification teams rely on these types of tools to design and develop Automated Test Equipment (ATE) to communicate and execute test cases. Some of the benefits they offer are tool standardization, database homogenization, system model reuse from software development teams among others.

These tools are excellent to design and develop large vehicle simulations and tests scenarios but once the test modes have been designed, users of these tools still need to have expensive Runtime licenses to execute their developed models. Sometimes these models are for Proof of Concepts purposes, test demos or small implementations that make it difficult to justify the purchase of a high-cost development or Runtime tool license.

The purpose of this Hardware-in-the-loop (HIL) test tool is to allow test developers to implement and execute their already developed test scripts without the need of Runtime licenses.

This project uses a development platform from ST Microelectronics which has a low cost but highly capable MCU. This MCU can communicate with any ECU via CAN and execute user defined test scenarios. The user communication to the HIL Test Tool is via Ethernet, the HIL Test Tool acts as TCP server so any TCP client can communicate with it and send command instructions to the Device Under Test (DUT).

This project was designed and built using the waterfall process methodology. The overall design of the system suits this deign well because the requirements are known and for demonstration purposes they will not change. A requirements phase, design phase, implementation phase and test phase were implemented and will be discussed in the following sections

The test modes in the other hand, were developed in sprints using Test Driven Development. Section XYZ describes the system development progress in the 3 main sections: Hardware, Software and Testing.

# Concept

The general purpose of this project is to emulate the functionality of an Automated Test Equipment (ATE) capable of running pre-defined test scenarios via CAN communication to any type of ECU that has CAN communication available. For this project, a basic vehicle CAN network consisting of 3 ECUs is simulated using Vector CANoe to demonstrate the functions of the HIL Test Tool.

The HIL Test Tool uses FreeRTOS as operative system to handle the different tasks (application code) to interact with the DUTs implemented in the simulated vehicle network in CANoe. The application code consists of 3 different tasks. Each task will execute a predefined Test Mode. The software architecture is modular so in case there is a need to add more test cases, the design pattern supports the addition of new tasks just by adding new tasks within freertos.c

The yellow box in *Figure 1* represents the CAN interface to allow physical devices to interact with the simulated network. Any TCP client can interact with the HIL Test Tool but for this project a custom TCP client was developed using NI LabVIEW to have a better interaction with the Test Tool.

*Figure 1* shows the overall concept of the project and the main project elements. The next section will describe the different requirements for the main project components.

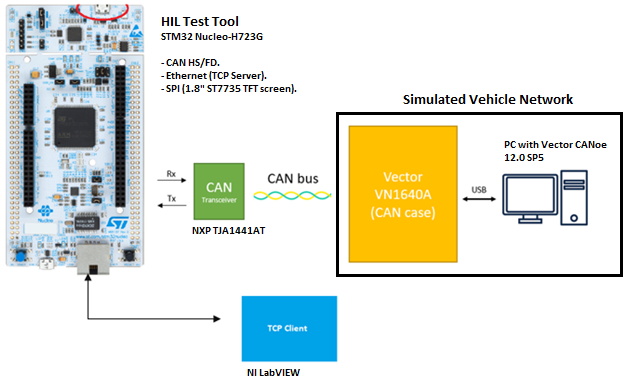
**

Figure 1. Project Elements: HIL Test Tool, Simulated CAN network and TCP client.

# REQUIREMENTS

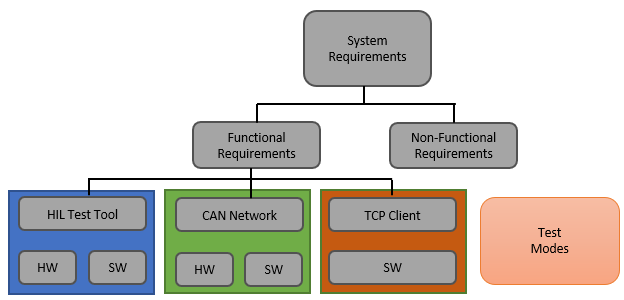
In this section, the system requirements for this project are shown and divided in 3 groups: HIL Test Tool, CAN Network and TCP client.

Figure 2. Overall System Requirements

## HIL Test Tool Hardware Requirements

| ID | HIL Test Tool Hardware Requirements | | |
| --- | --- | --- | --- |
| Name | Type | Description |
| HW-001 | Dev. Board | Functional | Board has 3 CAN HS/FD controllers. |
| HW-002 | CAN Transceiver | Functional | NXP TJA1441AT is used as Tx. |
| HW-003 | Ethernet Comm. | Functional | Board has Ethernet connection. |
| HW-004 | CAN termination | Functional | 120Ohm resistor used as termination. |
| HW-005 | Ethernet cable | Functional | CAT6 cable is used. |
| HW-006 | CAN Connector | Functional | A DB9 connector is used for PINs 2 & 7. |
| HW-007 | CAN cable | Functional | A twisted pair cable is used for comm. |
| HW-008 | LCD screen | Functional | Adafruit ST7735 1.8” display. |

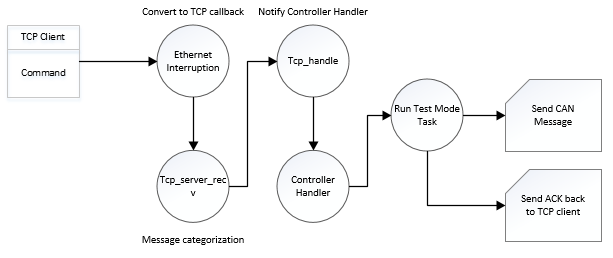
Table 1. HIL Test Tool Hardware Requirements.

| ID | HIL Test Tool Software Requirements | | |
| --- | --- | --- | --- |
| Name | Type | Description |
| SW-001 | RTOS | Functional | FreeRTOS is used |
| SW-002 | CAN bus speed | Functional | 500kbaud is configured |
| SW-003 | Serial COM | Functional | UART1 enabled |
| SW-004 | RT response | Functional |  |
| SW-005 | TCP Comm. | Functional | Board has a TCP server. |
| SW-006 | Software Arch. | Functional | Modular & scalable. |
| SW-007 | Test Scripts | Functional | Modular & scalable. |

Table 2. HIL Test Tool Software Requirements.

Figure 3 shows the path that data follows when a command is received by the HIL Test Tool, how is it processed by the TCP handle process and how the CAN message is sent to the network.

Similarly, figure 7 shows the Data Flow Diagram for the inverse process when the ECU responds back with the information via CAN needed to evaluate and apply PASS/FAIL criteria.



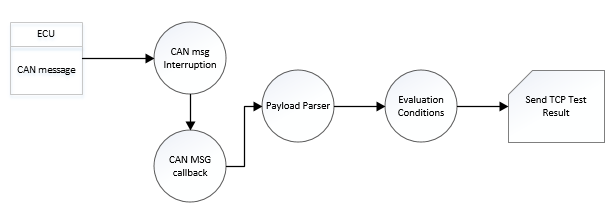
Figure 3. Data Flow Diagram for TCP message

Figure 4. Data Flow Diagram for ECU message response

## Simulated CAN Network Requirements

| ID | Simulated CAN Network Requirements | | |
| --- | --- | --- | --- |
| Name | Type | Description |
| SM-001 | CAN network | Functional | CAN network with at least 1 ECU. |
| SM-002 | ECU1: Engine | Functional | Read/write Speed signal |
| SM-003 | ECU2: Lights | Functional | Read/write Light & hazard signal |
| SM-004 | ECU3: Display | Functional | Read/write panel values. |
| HW-009 | CAN Interface | Functional | Vector VN case 1640 |

Table 3. Simulated CAN network Requirements.

## TCP Client Requirements

| ID | TCP Client Requirements | | |
| --- | --- | --- | --- |
| Name | Type | Description |
| TCP-001 | TCP Client UI | Functional | GUI design and developed in LV. |
| TCP-002 | Modular Design | Functional | Supports additional states. |
| TCP-003 | Known Design Pattern | Functional | State Machine based application. |

Table 4. TCP Client Requirements

## Test Mode Requirements

As seen in figure 2, the Test Mode requirements are a separate entity from the HIL test tool. This is expected because each project will have its own Test Plan and test requirements. For demonstration purposes a set of 4 test modes are included as part of this project.

| ID | Test Mode Requirements | | |
| --- | --- | --- | --- |
| Name | Type | Description |
| TM-001 | Speed Engine | Functional | Verifies the speed set to the ECU. |
| TM-002 | Lights | Functional | Verifies the lights turn ON/OFF. |
| TM-003 | Hazards | Functional | Verifies the hazards turn ON/OFF |
| TM-004 | Engine status | Functional | Verifies the ignition status of the engine. |

## Non-Functional Requirements

The system has several non-functional requirements. One of them is the time it takes a command to reach the HIL Test Tool. This time can vary widely based on the load of the local area network (LAN). A second variable would be the acknowledgment sent from the Test Tool back to the TCP client. The tool is designed to work with any TCP client in the market that can send a string of characters. As long as the client is able to read a string of characters it will display the status of the tool.

# Project Elements

This section describes the parts of the project that were used both in hardware and software.

## Hardware – HIL Test Tool

The Test Tool hardware consists of a Nucleo-H723ZG which has an STM32H7 (Arm 32-bit Cortex-M7) with 1 Mbyte of Flash and 320 Kbytes of RAM. The board has access to 1 CAN controller supporting flexible data rate. The CAN interface is configured as CAN High Speed (HS) only because the information required for the test mode does not require more than 8 bytes of payload.

To communicate with a CAN network, the TJA1441AT CAN transceiver from NXP was used. This transceiver supports up to 5 Mbit/s in FD mode. The configured speed for the CAN controller is 500 Kbytes.

To display the status of the Test Tool, a small 1.8” TFT screen (ST7735) was connected using SPI communication protocol. The bus speed is set to 6 MBits/s. SCK signal is connected to PA5 and MOSI signal is connected to PD7 of the development board.

## Hardware – Simulated CAN Network

The simulated CAN network provides the right environment to test the HIL Test Tool. A VN1640A CAN case from Vector was used as interface to connect the HIL Test Tool to the real CAN network.

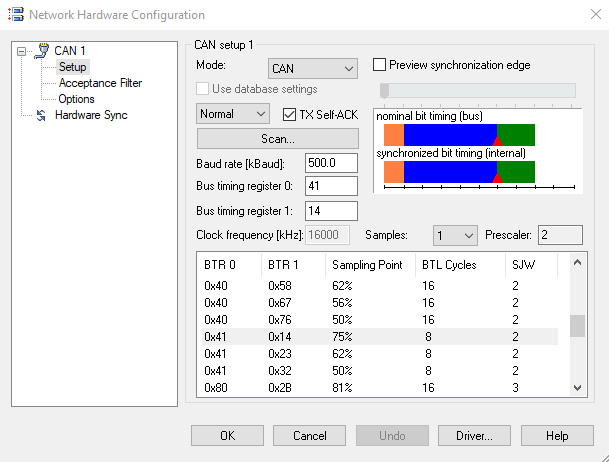
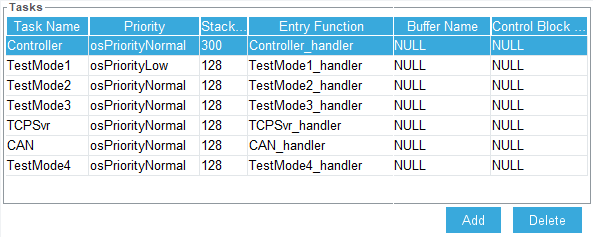
The VN1640A is a modular interface that supports CAN and LIN interfaces. CAN 2 channel was used as the CAN interface. The CANoe setup shown in Figure 5 was applied to achieve a 500Kbyte speed network.

Figure 5. CAN interface configuration in CANoe.

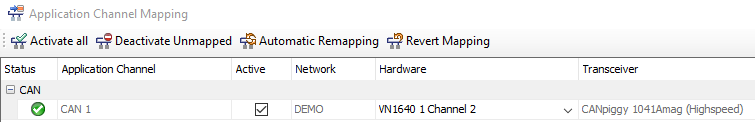
Figure 6 shows the mapping of the CAN channel number used to the interface with the ECU.

Figure 6. Physical CAN port mapping.

## Software – HIL Test Tool

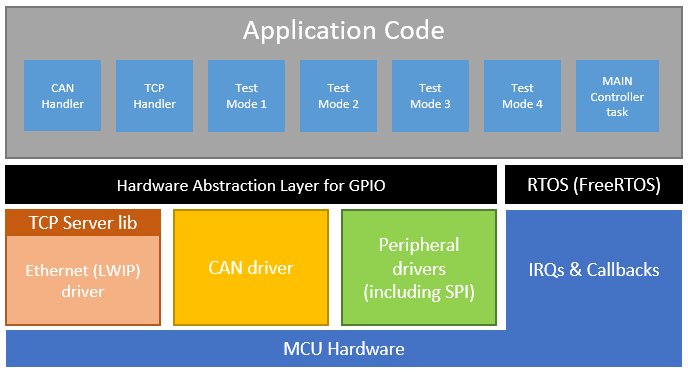
Software in the ECU uses a Real-Time Operative System (FreeRTOS) to handle the tasks of the project. Figure 7 shows the main software architecture.

Figure 7. HIL Test Tool software architecture.

Figure 8 summarizes the FreeRTOS tasks used in the project. Section V contains a detailed description of each task.

Figure 8. FreeRTOS tasks declared in STM32CubeIDE.

## Software – Simulated CAN Network (CANoe)

The simulated CAN network was implemented using Vector CANoe. CANoe is a commercial off-the-shelf software tool to develop, test and analyze individual ECUs and entire networks. It comes preloaded with examples to quickly start analyzing automotive networks.

The following CAN network was implemented based on one of the examples that came with the tool and was modified to show the data being sent to and from the HIL Test Tool. Figure 8 shows the complete CAN network and the 3 ECUs (Engine, Light and Display).

The Engine ECU handles the ignition status as well as the speed of the vehicle. The Light ECU is in charge of handling the headlights and hazards of the vehicle and the Display ECU handles the indicators of the panels showing the speedometer and the rest of the indicators of the panels.

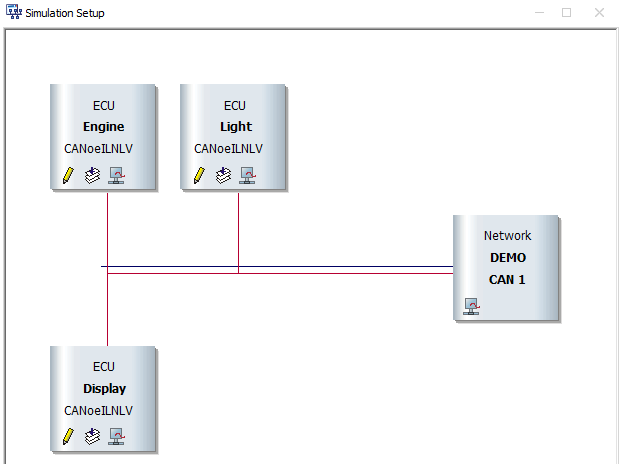


Figure 8. Simulated CAN Network.

# Design

This section describes the design approach used for the project. The project has 3 sections: Hardware, Software and Test. Figure 9 shows the flow diagram for each area of the project.

## Project Development Process

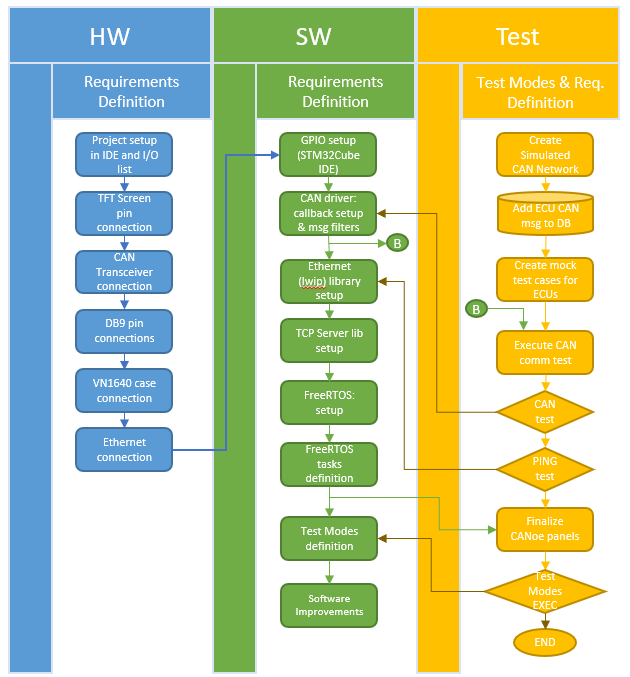


Figure 9. Flow Diagram for Task development.

The system development process that was chosen based on the requirements was

## Software Design

### Controller Area Network

### Ethernet/TCP Server

### GPIO

### Real Time Operative System

The chosen OS was FreeRTOS. FreeRTOS provides a lightweight RTOS and allows modularization of tasks making it a good framework for this project.

### Tasks

A total of 7 RTOS tasks were created. Controller\_handler, . All the tasks are in freertos.c

#### Controller Handler

This is the main task of the application code,

### Interruptions

## Test Modes

# Test Results

# CONCLUSIONS

##### References

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 A-D 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 use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

## Abbreviations and Acronyms

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, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

## Units

* 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/m2” or “webers per square meter”, not “webers/m2”. Spell out units when they appear in text: “. . . a few henries”, not “. . . a few H”.

Identify applicable funding agency here. If none, delete this text box.

* Use a zero before decimal points: “0.25”, not “.25”. Use “cm3”, not “cc”. (*bullet list*)

## Equations

The equations are an exception to the prescribed specifications of this template. You will need to determine whether or not your equation should be typed using either the Times New Roman or the Symbol font (please no other font). To create multileveled equations, it may be necessary to treat the equation as a graphic and insert it into the text after your paper is styled.

Number equations consecutively. Equation numbers, within parentheses, are to position flush right, as in (1), using a right tab stop. 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* 

Note that the equation is centered using a center tab stop. Be sure that the symbols in your equation have been defined before or immediately following the equation. Use “(1)”, not “Eq. (1)” or “equation (1)”, except at the beginning of a sentence: “Equation (1) is . . .”

## Some Common Mistakes

* The word “data” is plural, not singular.
* The subscript for the permeability of vacuum **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 [7].

# Using the Template

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

## Authors and Affiliations

**The template is designed for, but not limited to, six authors.** A minimum of one author is required for all conference articles. Author names should be listed starting from left to right and then moving down to the next line. This is the author sequence that will be used in future citations and by indexing services. Names should not be listed in columns nor group by affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization).

### For papers with more than six authors: Add author names horizontally, moving to a third row if needed for more than 8 authors.

### For papers with less than six authors: To change the default, adjust the template as follows.

#### Selection: Highlight all author and affiliation lines.

#### Change number of columns: Select the Columns icon from the MS Word Standard toolbar and then select the correct number of columns from the selection palette.

#### Deletion: Delete the author and affiliation lines for the extra authors.

## 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. Styles named “Heading 1”, “Heading 2”, “Heading 3”, and “Heading 4” are prescribed.

## Figures and Tables

#### 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. 1”, even at the beginning of a sentence.

1. Table Type Styles

| Table Head | Table Column Head | | |
| --- | --- | --- | --- |
| Table column subhead | Subhead | Subhead |
| copy | More table copya |  |  |

1. Sample of a Table footnote. (*Table footnote*)
2. Example of a figure caption. (*figure caption*)

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 *(Heading 5)*

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

The template will number citations consecutively within brackets [1]. The sentence punctuation follows the bracket [2]. Refer simply to the reference number, as in [3]—do not use “Ref. [3]” or “reference [3]” except at the beginning of a sentence: “Reference [3] was the first ...”

Number footnotes separately in superscripts. Place the actual footnote at the bottom of the column in which it was cited. Do not put footnotes in the abstract or reference list. Use letters for table footnotes.

Unless there are six authors or more give all authors’ names; do not use “et al.”. Papers that have not been published, even if they have been submitted for publication, should be cited as “unpublished” [4]. Papers that have been accepted for publication should be cited as “in press” [5]. Capitalize only the first word in a paper title, except for proper nouns and element symbols.

For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation [6].

1. G. Eason, B. Noble, and I. N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955. *(references)*
2. J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.
3. I. S. Jacobs and C. P. Bean, “Fine particles, thin films and exchange anisotropy,” in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.
4. K. Elissa, “Title of paper if known,” unpublished.
5. R. Nicole, “Title of paper with only first word capitalized,” J. Name Stand. Abbrev., in press.
6. Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, “Electron spectroscopy studies on magneto-optical media and plastic substrate interface,” IEEE Transl. J. Magn. Japan, vol. 2, pp. 740–741, August 1987 [Digests 9th Annual Conf. Magnetics Japan, p. 301, 1982].
7. M. Young, The Technical Writer’s Handbook. Mill Valley, CA: University Science, 1989.

**IEEE conference templates contain guidance text for composing and formatting conference papers. Please ensure that all template text is removed from your conference paper prior to submission to the conference. Failure to remove template text from your paper may result in your paper not being published.**

We suggest that you use a text box to insert a graphic (which is ideally a 300 dpi TIFF or EPS file, with all fonts embedded) because, in an MSW document, this method is somewhat more stable than directly inserting a picture.

To have non-visible rules on your frame, use the MSWord “Format” pull-down menu, select Text Box > Colors and Lines to choose No Fill and No Line.