2024-2025 2DX3 PROJECT SPECIFICATION – OBSERVE, REASON, ACT: SPATIAL MAPPING USING TIME-OF-FLIGHT

1. Introduction

You are to design and build an embedded spatial measurement system using a time-of-flight sensor to acquire information about the area around you. Using a rotary mechanism to provide a 360 degree measurement of distance within a single vertical geometric plane (e.g., y-z), you must integrate fixed distance samples along the orthogonal axis (e.g., x-axis). Mapped spatial information is stored in onboard memory and later communicated to a personal computer or web application for reconstruction and graphical presentation.

2. Rationale

Commercial Light Detection and Ranging (LIDAR) equipment is expensive and bulky. Our application requires a less expensive and smaller custom system that is suitable for indoor exploration and navigation. For most engineers, at some point in their career they will need to acquire data. Often there are numerous systems available, but they can be expensive, limited in capability, and/or too complex for your requirements. As a result, data acquisition becomes too complex or expensive. Ultimately, engineers seek to measure physical phenomenon accurately at as low a cost possible.

The experience with this project will also give the student insight into how the commercial/industrial data acquisition systems operate.

One of the primary objectives of 2DX is that the student gains the capability to collect data using the microcontroller and then be able to process and communicate that data. This knowledge will be directly applicable to future design courses, most senior capstone projects, and certainly beyond.

3. Overview

For this project you will be working though a design-test-build approach for the development and demonstration of a data acquisition system. It is strongly recommended to work through lectures, studios, labs, and assigned work to complete the recommended milestones. Keeping up with milestones is your best opportunity to do well on the project.

4. Technical Requirements

The overall design of a data acquisition system project was described in lecture when introducing the Analog-to-Digital Converter module. The required tasks, corresponding to the steps illustrated in figure 1, are:

: **Quantify the analog signal** - range of amplitude, frequency, source, impedance [continuous signal].

: **Build/Select the appropriate transducer** - pressure, sound, temperature, etc.

: **Precondition signal** - amplify, filter, and/or level shift to conform to ADC design.

: **Analog-to-Digital Conversion (ADC)** - determine voltage range (min, max), resolution, sampling frequency [discrete data].

Date: Updated: December 23, 2024 @ 1527.

: **Data processing** - read data from ADC and store/process/transmit under time constraints to return to the ADC for the next conversion.

: **Control/Communicate** - implement an algorithm that meets the objective with hardware and timing constraints.

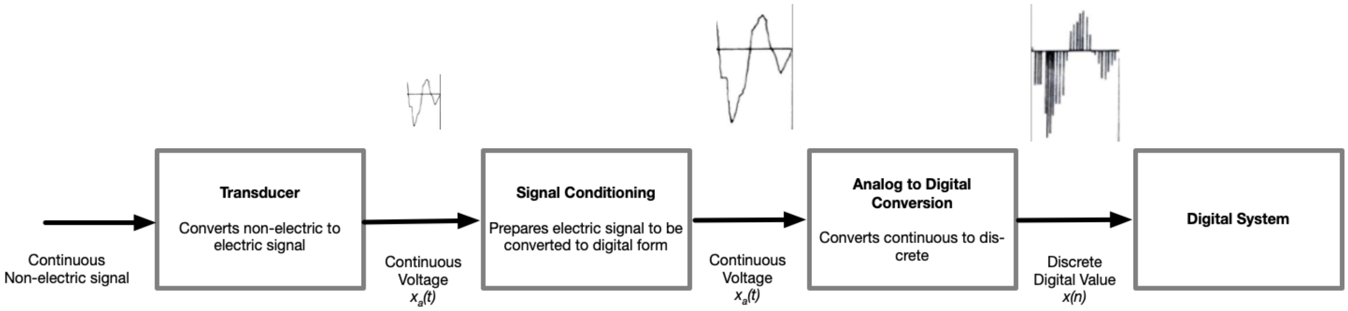

FIGURE 1. The ADC process

For this project we have selected a transducer that provides a digital output. Thus, the data acquisition steps can be thought of as being included in the transducer block as shown in figure 2. You will have to study the transducer closely to understand the data that it produces and to integrate it with the rest of your system, including design decisions about data processing.

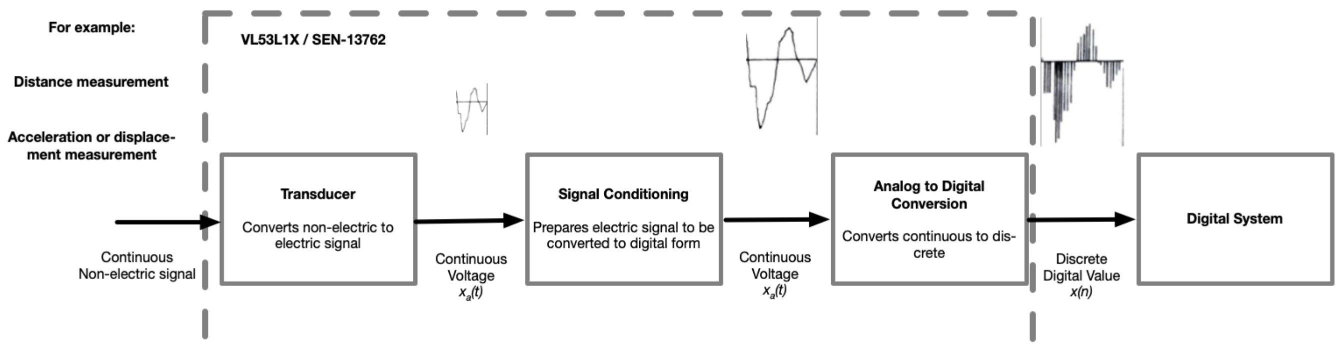

FIGURE 2. The ADC process

There are two types of distance measurements we could collect: spatial distance (y-z plane) and displacement (x-axis). For our project we will only me measuring the spatial distance and setting a fixed displacement. Combining the two will permit us to measure a 3-D area (x,y,z).

To measure the planar spatial distance you will be using the VL53L1X Time of Flight (ToF) sensor on a predesigned breakout board[1]. This sensor will be mounted to a stepper motor for that will rotate the sensor through 360 degrees while collecting measurements. Note that the data sheet for the ToF sensor lists three distance modes: 136cm (4.5ft), 290cm (9.5ft), and 360cm (11.8ft). Selecting the mode is one of the design decisions you will have to make for your project implementation. For all communication between the ToF sensor and the microcontroller, you will use a serial interface (I^2C).

For displacement you should move your stepper motor/time of flight sensor combo manually and gather readings at regular distances (e.g. every 30 cm).

[1]Important note: This product might ship with a protective liner covering the sensor IC. The liner must be removed for proper sensing performance.

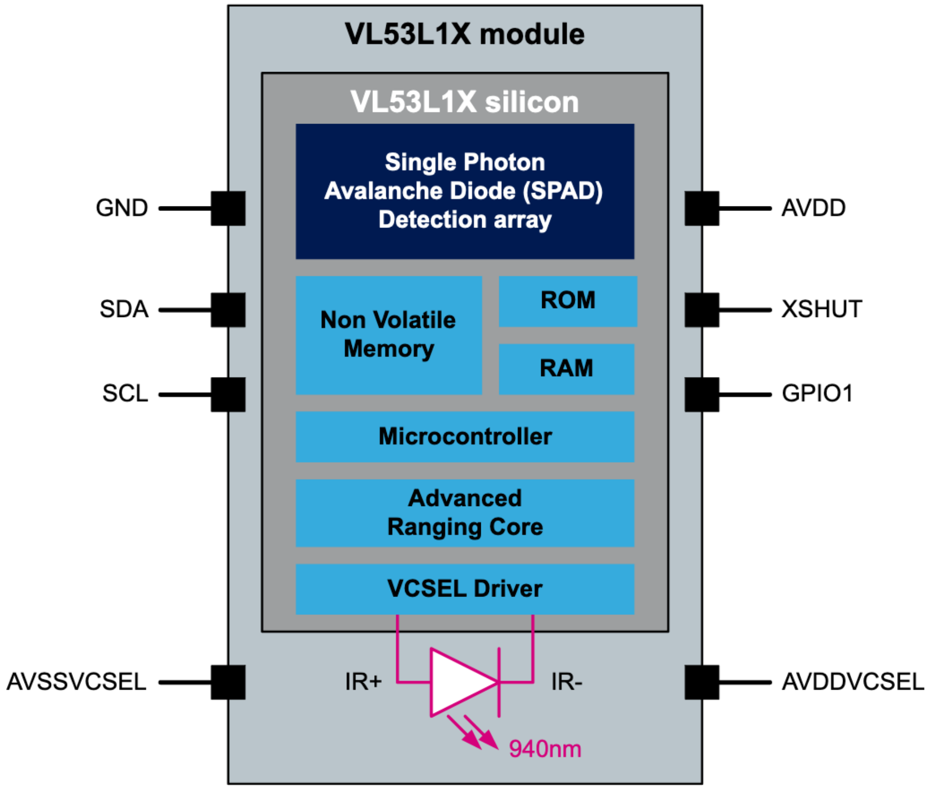

FIGURE 3. Time of flight (ToF) breakout board

You will need to consider the assembly of these components as a part of your final design – this may require minor construction with wood, plastic, 3D printing, Lego pieces, etc. for which you are responsible.

Figure 4 shows an example of how the stepper motor and the ToF sensors are mounted using Lego and a shoe box.

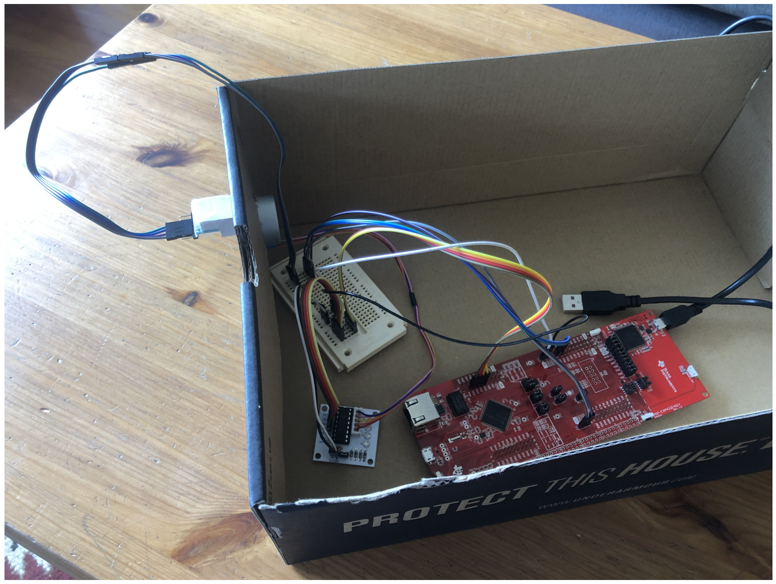

FIGURE 4. A mounting option

4.1. **Core Components.** The technical requirements of this project are to build an embedded system which integrates measurement modalities and device control such that it can be used to map indoor environments, such as hallways, for use as a component of other systems (e.g., robotics navigation, autonomous drone, layout mapping, etc.). The components required are:

(1) Digital I/O: Momentary push button to start and stop data acquisition process

(2) Digital I/O: Momentary push button to start and stop the stepper+ToF rotation and measurement

(3) Digital I/O: LED status of each distance measurement

(4) Digital I/O: LED for additional-status and/or troubleshooting

(5) Transducer/sensor 1: ToF sensor to measure distance of vertical plane (e.g., y-z plane)

(6) Data processing: coordinate collection, computation, and storage of distance and displacement

(7) Manually activate collection of new distance data (360 degrees) once defined fixed displacement reached

(8) Implementation mode: polling or interrupt design

(9) Control: control the rotation of the stepper motor to support ToF sensor

(10) Communicate/Control: communicate data between ToF sensor and microcontroller.

(11) Map an instructor defined location on campus based on student number. This information will be posted via Avenue.

(12) Communicate: communicate stored distance and displacement data to PC application

(13) Communicate: communicate data to PC application to graphically view data (Student choice of non-autographing application: Matlab, Java, Python etc.). Alternatively, generating a 3D model in standard file formats (e.g., STL) may use pre-existing software packages to display the model (e.g., Autodesk Inventor Viewer, MS 3D Viewer, etc.)

An example of a graphical view of data is shown in 5.

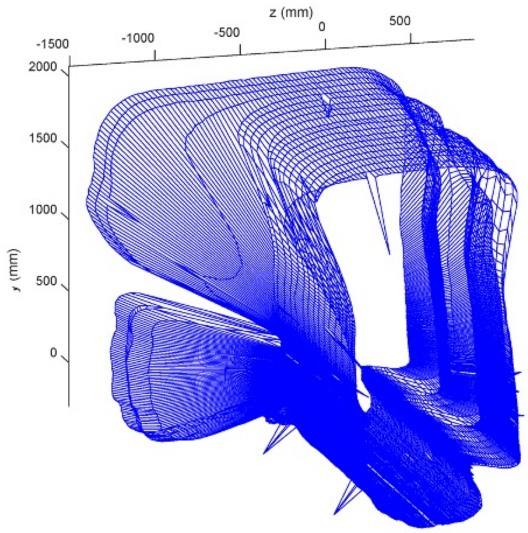

FIGURE 5. Graphical reconstruction of 3D mapping of a hallway

The project must acquire spatial data (control the stepping motor + ToF + status LED + manual displacement) of an instructor defined location, process the data, serially transmit the waveform data to a PC, and graphically display this data as a 3D model. The student must be able to **start and stop** data acquisition using a physical momentary push button. LED status shall be presented realtime. The use and configuration of the ToF will be addressed in lab, lecture, and studio. If you would like to read ahead on these devices, please review:

ToF sensor (VL53L1X) datasheet: `https://www.pololu.com/file/0J1506/vl53l1x.pdf`

4.2. **Student Specific Requirements.** Based upon student number, each student will be assigned different operational parameters. The example student number 123456789 (ABCDEFGHJ) will be used to illustrate each assigned parameter (written as a string of letters to refer to digit position instead of digit value). Please refer to lecture notes if you are not sure what is meant by LEAST SIGNIFICANT DIGIT (LSD) or MOST SIGNIFICANT DIGIT (MSD). These terms refer to positional notation and NOT the value of the number. For example, the LSD of the example student number is POSITION J (=9).

4.2.1. *Individualized Operational Parameters.*

Bus Speed: The default bus speed is 120MHz. Based upon the least significant digit "J" (remember, this refers to positional notation) of your student number you are to use the following bus speed – see Table 1.

Digital I/O LED Measurement Status: Distance measurement requires an LED for status indication. Based upon the second least significant digit "H" (remember, this refers to positional notation) of your student number you are to use one of the following on-board GPIOs (PN0, PN1, PF0, or PF4) – see Table 2.

Digital I/O LED Measurement Status: UART Transmission indication. At the beginning of a transmission block flash the defined LED. It is not necessary to flash the LED for every byte transmitted. Based upon the second least significant digit "H" (remember, this refers to positional notation) of your student number you are to use one of the following on-board GPIOs (PN0, PN1, PF0, or PF4) – see Table 2.

Digital I/O LED Additional Status: Additional and/or troubleshooting status requires an LED for status indication. You are to choose a meaningful aspect of the project that is not already specified and based upon

Table 1. Individualized bus speed based upon least significant digit of student number "J"

Least Significant Digit	Assigned Bus Speed (MHz)
0	12
1	16
2	20
3	22
4	24
5	18
6	14
7	10
8	26
9	12

the *second least significant digit* "H" (remember, this refers to positional notation) of your student number you are to use one of the following on-board GPIOs (PN1, PN0, PF4, or PF0) – see Table 2

Table 2. Individualized LED status GPIO based upon second least significant digit of student number "H"

Second Least Significant Digit	Measurement Status	UART Tx	Additional Status
2	PN0	PN1	PF4
4	PN1	PF4	PN0
6	PF4	PF0	PN0
8	PF0	PF4	PN1
0	PF4	PN1	PF0
1	PN1	PF4	PN0
3	PF4	PF0	PN1
5	PF0	PN0	PN1
7	PN1	PN0	PF4
9	PN0	PN1	PF4

4.3. **Physical Demonstration Location.** For early prototype testing use a room or a hallway to which you have easy access and can verify dimensions. This early testing location should have a few notable changes that your system can capture. You will be assigned a physical testing location on McMaster's main campus.

In addition, you should expect to be asked to demonstrate scanning and 3-D mapping functionality as component of your final interview.

5. Documentation

Rather than a formal technical report, your documentation will be formatted as a data sheet and application note for your system that would be suitable for another engineer like yourself.

Consider some of the questions for inclusion in your documentation:

(1) Summarize any limitations of the microcontroller floating point capability and use of trigonometric functions.

(2) Calculate your maximum quantization error for each of the ToF module.

(3) What is the maximum **standard** serial communication rate you can implement with the PC. What speed did you implement and how did you verify?

(4) What were the communication method(s) and speed used between the microcontroller and the ToF modules?

(5) Reviewing the entire system, which element is the primary limitation on system speed? How did you test this?

(6) Show the steps and calculations to configure your assigned system Bus Speed from Table 1.

6. Milestones & Deliverables

As a second year student you are expected to set your own goals and timeline for completion for the final project – a Gantt chart should be generated for your own scheduling. Your project will be tested for performance and you will demonstrate your knowledge about the project. Afterwards your documentation and files will be assessed.

The following are suggested milestones for your own progression. Deliverables are noted for interview and demonstration of project at the 1) early integration point, and 2) end of the development.

Refer to the graphical course map to see when milestones are suggested to be completed. The list below each milestone is a suggested check-list for your planning of tasks.

6.1. Milestone 1.

- ☐ Review the project specification.
- ☐ Identify target objectives based on your student number.
- ☐ Review available resources (e.g., pins) on the microcontroller board and record/map the initial pin layout.

6.2. Milestone 2.

- ☐ Establish a working push button and LED program.
- ☐ Generate a pin-assignment map.

6.3. Milestone 3.

- ☐ Establish a working stepping motor program.
- ☐ Have time left in lab? Work on your Deliverable 1 and project requirements.

6.4. Milestone 4.

- ☐ Early integration – establish a working stepping motor + start/stop push button + LED status program.
- ☐ Have time left in lab? Work on your Deliverable 1 and project requirements.

6.5. Deliverable 1 - Early Project Integration Demonstration. For this deliverable :

- ☐ Review Instructions for Deliverable 1 in the Lab Manual under Lab 6.
- ☐ Confirm you have a scheduled interview time.
- ☐ As per the specification in the lab manual you should be able to demonstrate:
  (1) Push button for Start/Stop with status LED,
  (2) Push button for Motor Direction with status LED,

(3) Push button for Angle selection with status LEDs,

(4) Push button for Homing function.

- ☐ Attend the scheduled interview and project milestones demonstration.

6.6. **Milestone 5.**

- ☐ Establish a working button (you may use a polling or interrupt(s) method).
- ☐ Establish I2C and UART protocols.
- ☐ Establish a working fixed-position ToF
- ☐ Establish a working serial communication with PC and display measurement data (terminal, etc.).
- ☐ Establish and test 3D modelling protocol and format.
- ☐ Integration of functional modules
- ☐ Have time left in lab? Work on your project requirements.

6.7. **Deliverable 2.** For this deliverable, please note the following:

- ☐ Review Instructions for Deliverable 2 in Section 8
- ☐ Confirm you have a scheduled interview time.
- ☐ Attend the scheduled interview and project milestones demonstration.
- ☐ Review section on Bonus marks and eligibility in Section 10
- ☐ Refer to Section 11 Submission Requirements.
- ☐ Submit final report by Tuesday April 8 at 11:55 pm (firm deadline). See Section 9.

7. Instructions for Deliverable 1

Deliverable 1 is almost identical with Milestone 4 in your project; however, unlike Milestone 4, the deliverable does not require the use of Individualized Operational Parameters.

You will have to do a demo and an interview according to the details below.

7.1. **Logistics.**

(1) The interview schedule is posted under `Content->Administrative`. Please always consult the latest version posted. The schedule tells you the time and location for your interview.

(2) You should arrive 10-15 minutes before your scheduled time.

(3) You should already have as much of your deliverable setup as possible.

(4) You will be allowed into the lab 10 minutes before your scheduled time to complete your setup. You will not have a large area in the lab to setup so you have to have most of it already done and work efficiently and neatly to get ready to demo your work.

(5) At your scheduled time, you will be asked to move to your station where a TA will be available to assess your work.

(6) If you are not ready to start on time, this cuts into your own time. We will not extend the end time for your interview. Your grade will be based on how much can be done during the available time.

(7) Your demo and interview together are 10 minutes long.

7.2. **Demonstration.** Please refer to the lab manual for the specification of the early integration platform for demonstration.

7.3. **Interview.** You will be asked approximately questions regarding your project. Questions examples could include: how you implemented each of the specification requirements, how the stepper motor works, how a push button works, how you would alter the hardware or the code to operate differently (e.g. how to make your buttons active low or active high; how to change the direction of rotation; etc.), or other similar questions.

Questions could also be about thinking ahead to future project deliverables. E.g. when you implement a student specific clock speed, what parts of your current code would be impacted? What debugging might be useful to use a 2nd LED for?

Each student will be asked several questions and those questions will not be the same questions for each student.

The grading for the questions will be on four levels:

- Below expectations: no answer; factually wrong answer; or very unclear answer (0%)
- Marginal: a basically correct but incomplete answer (50%)
- Meets expectations: the answer is correct and complete (100%)
- Exceeds expectations: a concise answer that demonstrates a deep understanding of the design, including precise use of terminology (105%)

Once your demo and interview are done, please leave the lab within 5 minutes to allow other students to continue with their interviews without delay.

8. Instructions for Deliverable 2

Deliverable 2 is your project's final in-person deliverable and is almost identical with Milestone 5 in your project.

You will have to do a demo and an interview according to the details below.

8.1. **Logistics.**

(1) The interview schedule is posted under `Content->Administrative`. Please always consult the latest version posted. The schedule tells you the time and location for your demo and interview.

(2) You should arrive 10-15 minutes before your scheduled time.

(3) You should already have as much of your deliverable setup as possible.

(4) You will be allowed into the lab 10 minutes before your scheduled time to complete your setup. You will not have a large area in the lab to setup so you have to have most of it already done and work efficiently and neatly to get ready to demo your work.

(5) At your scheduled time, you will be asked to move to your station where a TA will be available to assess your work.

(6) If you are not ready to start on time, this cuts into your own time. We will not extend the end time for your interview. Your grade will be based on how much can be done during the available time.

(7) Your demo and interview together are 15 minutes long.

8.2. **Demo.** The items below are intended to clarify and provide more detail. There should be no contradiction between the items below and what is in the current project specification. If there is a contradiction, the project specification is correct.

(1) You have been assigned a specific location on campus to scan - this must be scanned and plotted prior to your c
Ensure you bring this scan plot and a photo of the scanned space to the interview presented as a side-by-side comparison on a single page (include as an appendix to your final report).

(2) Attend your assigned scheduled interview time. You are expected to be available to start setting up your project 10 minutes prior to your scheduled start time. Your interview is scheduled for a specific time and you will not be permitted additional time due to missing your set up time.

(3) For the functional demonstration of the interview:

   (a) For full integration, demonstrate and explain your system process:

      (i) Using a button to start your system, scan the interior of the lab apparatus 3x (no displacement, just scan same position 3 times).

      (ii) Based on scanned data show 3D representation of the apparatus interior.

   (b) ToF demo and explanation (if (a) was successful in demonstration then you only need to explain).

   (c) I2C and UART communications demo and explanation (if (a) was successful in demonstration then you only need to explain).

   (d) Prove you have achieved assigned bus speed.

   (e) Demonstrate the assigned LEDs.

Your performance for demonstration is critical. If you cannot explain it, you don't get the credit for it. Each functional component will be assessed based on:

- Correctly working and fully integrated: 100%
- Incorrect but partially functional OR component working but not integrated: 50%
- Component is not functional: 0%.

8.3. **Interview.** You will be asked approximately 3 questions regarding your project. Questions could be about how you implemented each of the above requirements, how some aspect of the hardware works (for example, stepper motor, push buttons, ToF sensor, UART/I2C communication protocols, and so on), how some aspect of the software works (for example, how you integrated codes from various studios in your project, how was your assigned bus speed achieved, and so on), and similar questions.

Questions could also be about how you might expand the capabilities of your project further in the future or what if you were presented with a different set of requirements, how would you go about achieving those goals? Questions might also make links with real world scenarios that rely on embedded systems and whether you can extrapolate the knowledge that you have gained in this course and project to these real world scenarios.

Each student will be asked several questions that will not be the same for each student. The grading for the questions will be on four levels:

(1) Below expectations: no answer; factually wrong answer; or very unclear answer (0%)

(2) Marginal: basically a correct but incomplete answer (50%)

(3) Meets expectations: the answer is correct and complete (100%)

(4) Exceeds expectations: a concise answer that demonstrates a deep understanding of the design, including precise use of terminology (105%)

Once your demo and interview are done, please leave the lab within 5 minutes to allow other students to continue with their interviews without delay.

9. Final Report Format

Your document should be structured similar to a datasheet with an Application Note. Your document must have the following sections, describing your project as a product:

(1) Device Overview (Approximately 1.5 pages)
   (a) Features
   (b) General Description
   (c) Block Diagram (Data flow graph)
(2) Device Characteristics Table (Focus on user's technical "need to know") (Approximately 0.5 pages)
(3) Detailed Description (Be concise) (Approximately 3 pages)
   (a) Distance Measurement
   (b) Visualization
(4) Application Note, Instructions, and Expected Output. This section must include steps to TA to use/setup your product without you and have a side-by-side comparison of your assigned campus location photo vs. your 3D model based on your scanned data. (Approximately 3-4 pages)
(5) Limitations (Answers to specification questions) (Approximately 1 pages)
(6) Circuit Schematic
(7) Programming Logic Flowchart(s)

9.1. **Typesetting Format.** The final report should be presented as a technical specification that must be complete, organized, and concise. As a guide, we do not expect the body of the report to exceed 9 pages (excluding schematic and flowcharts).

Font should be Times Roman, body and label text should be 12 pt, section headings should be 14 pt, and Title should be 18 pt. Margin should be no larger than 1in. Text should be single spaced and presented in a single or double column. Hand drawn images, calculations, etc. are not acceptable. Citations should follow the IEEE format. Should a student wish, s/he may typeset in LaTeX.

10. Final Project Bonus

The following are a list of bonuses available to students that meet and demonstrate all above core design requirements. Please do not jeopardize core objective grades in pursuit of bonus marks. These bonus marks will be applied up to a maximum of 110% of the final project grade.

10.1. **Bonus 0. After meeting all above core design requirements** assigned to the student, a 5% will be given to any student that implements a fully functional project implementing and demonstrating a self-resetting or "homing" functionality for the stepper-ToF sensor. You will need to define the home position (i.e., 0 degrees) of stepper-ToF sensor to reconstruct the spatial measurements. At each displacement along the x-axis the stepper-ToF sensor will conduct a y-z scan of the area. If the scan process stops mid-scan then your system will return the stepper-ToF sensor to its home position and then permit the scanning to continue. You may assume the power remains on and no reset has occurred.

10.2. **Bonus 1 – Meeting Required. After meeting all above core design requirements** assigned to the student, a 5% will be given to any student that implements a fully functional project implementing and demonstrating an additional sensor that meaningfully enhances the core project objectives. For example, a real-time distance measurement (e.g., continuous displacement instead of fixed displacement measure of y-z distance). Bonus marks are only awarded to projects that have first met all core objectives (this may require two version of project). ***You must write a brief proposal and speak directly to one of the course professors to approve this bonus prior the end of week 6.***

10.3. **Bonus 2 – Meeting Required. After meeting all above core design requirements** assigned to the student, a 10% will be given to any student that implements a fully functional project implementing and demonstrating an automatic "hands-free" linear translation for full data collection. For example, you add a mechanical system and your own necessary code to your project that allows automatic collection of all data measurements in the scanning of a physical location. Bonus marks are only awarded to projects that have first met all core objectives (this may require two version of project). ***You must write a brief proposal and speak directly to one of the course professors to approve this bonus prior the end of week 6.***

11. Submission Requirements

Each student will be required to demonstrate their final project and answer interview questions. **Any project that is not accompanied by a complete final report will be assigned a 0 for the entire project.**

Students should expect to demonstrate how well their project meets the specification and clearly answer specific questions about their design choices and implementation of the project. If the student cannot (or does not) answer or defend a design choice then no marks will be awarded for that portion.

Submit the following items to Avenue (separately) by the defined deadline:

(1) Final report - as outlined above. Must be a single file and in PDF format.

(2) Zipped file containing all source code (commented and templated). Must use the .zip compression. Test your compressed file, if it cannot be opened by us then we will not accept another submission after the deadline.

Any student choosing not to demonstrate the project, submit the a complete final report, and/or full set of executable code will be considered a late submission. Once penalties accumulate to 100% of the entire project, the work cannot be accepted for evaluation. Similarly, an interview/demonstration that is MSAFed will be rescheduled; however, given this project will have been posted for several weeks, the associated report and files must be submitted by the specified due date. Should a rescheduled interview be missed, the entire project will be assigned a 0. You must be able to demonstrate and defend your project design AND submit all files (report and code) for our review.

12. Changelog

The following changes were recorded:

(1) Released Jan 15, 2025

References