MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

EE493: ENGINEERING DESIGN 1, DESIGN STUDIO 9

CONCEPTUAL DESIGN REPORT

COMPANY: NATIONAL ELECTRONICS & SEMICONDUCTOR TECHNOLOGIES

PROJECT: GIMME FAST

ADVISOR: SINAN KORKAN

EMAIL: KORKANS@GMAIL.COM

PHONE: +90 555 555 5555

By

Shareholder	ID Number	Phone Number	E-mail
Yunus Emre İKİZ	2263671	+90 (543) 598 43 80	yunus.ikiz@metu.edu.tr
Rafet KAVAK	2166783	+90 (546) 505 64 00	rafet.kavak@metu.edu.tr
Ömer Can KARAMAN	2166775	+90 (543) 279 19 69	karaman.can@metu.edu.tr
Ersin KESKİN	2166817	+90 (537) 308 24 14	ersin.keskin@metu.edu.tr
Ayşegül KILIÇ	2262673	+90 (545) 514 02 01	aysegul.kilic@metu.edu.tr

DATE OF SUBMISSION**:** 20 DECEMBER 2019
STARTING DATE OF THE PROJECT**:** 02 OCTOBER 2019
ESTIMATED COMPLETION TIME OF THE PROJECT**:** 220 DAYS
THE COST OF THE PROJECT**:** 200 $

TABLE OF CONTENTS

1. Executive Summary

General Information and Purpose

Visible Light Communication (VLC) can be 100 times faster than today's communication technologies like Wi-Fi, etc., because light travels at extreme fast speeds compared to the radio waves. Also, the visible light spectrum is 10.000 times larger than the entire radio spectrum and this allows to have access to a greater range of available frequencies. For this reason, National Electronics and Semiconductor Technologies (NESET) Incorporation is dedicated to prove the advantages of VLC by delivering a ready to install VLC device packages as well as a complete demonstration setup for full customer satisfaction and inspection. NESET Inc. consists of a highly motivated engineering team with comprehensive work background presented in Team Organization.

In this project, transmission of the images (in packets) with two complementing technologies which are transportation and communication was aimed. In NESET's perspective, these objectives can be achieved by a product that consists of mainly 3 subsystems:

- Transmitter Terminal, which takes the image and transmits to the carrier.
- Carrier, which transports the data between terminals.
- Receiver Terminal, which reconstructs and shows the image.

From taking of the image at the beginning to reconstructing it back and displaying it in the receiver side, all processes were planned very detailed by NESET Inc. as can be seen throughout the report. Basically, the image was taken and divided into chunks at first. Then, by using Universal Asynchronous Receiver/Transmitter (UART) communication technology, data packets were transmitted between terminals and the carrier. At the end, all data packets will be reconstructed and displayed at the receiver side.

Results and Analysis

Up to now, NESET Inc. successfully completed data transmission between diodes and phototransistors under various environmental lightning conditions. Also, the carrier vehicle and its algorithm for soft start/stop were completed.

From now on, NESET Inc. will focus on transmission of the image chunks and handshake protocols for the completion of the project.

Conclusions

It is possible to build an VLC device with its implementation on a terminal-to-terminal communication demonstration via a helper robot by utilizing the allowed financial source and time. Resources provided (200$) for the project are considered sufficient to acquire the necessary computer hardware, microcontrollers, sensors and building material. The end product of this product not only offers a fully operational test setup but also portable OWC modules that can be installed in other computer hardware with standard serial communication (UART) capability. NESET Inc. also offers installation guidance and product warranty up to 2 years. It is also desired to contribute to the research academia by publishing academic research outcomes of this project.

2. Introduction

Having originated from beacon fires and carrier pigeons of ancient times, wireless communication has evolved into a high-capacity complementary technology to provide links between people. As witnessed in the last two decades, the demand for wireless data networks has increased exponentially with the increasing popularity of private computers and smartphones.

The primary basis of network relies on RF communication today as it possesses high agility and vast range. However, its networking capabilities are becoming to fall short day by day with the increasing demand for data. By 2015, it was expected that the total wireless data traffic would reach 6 exabytes per month, creating a potentially %97 gap between the demand and the available data in mobile networks. Consequently, complementary wireless transmission techniques were to be explored. One such alternative is Optical Wireless Communication (OWC). As a product, Project “Gimme Fast” sets the groundwork for the possible utilization of OWC using visible light as a communication medium. The project also provides a powerful demonstration of data transfer via OWC between remote sites to deny the argument that OWC is not possible over long distances. In this project, it is aimed to have a broad understanding of this emerging alternative wireless communication and provide solid know-how for future product applications.

The organization of the report is as follows. First the problem statement with desired system requirements is presented. Solution section is divided into multiple parts. The overall block diagram allows a broad view of the system. The main controller logic is presented in an Algorithmic State Machine chart and it is explained in detail with available input and output sources to control the algorithm. Then each subsystem is investigated with its description, requirements and proposed solution. Tests conducted and their results are also discussed in the solutions, followed by alternative solutions proposed and technical specifications of the system. Future work plans, foreseeable difficulties, future test and integration plans, cost analysis and deliverables are presented in the Plans section. Finally, the conclusion provides a recap of what has been done and what is to be done until finalizing our product.

2.1. Problem Statement

The importance of alternative solutions to remote communication has increased significantly due to the increasing population of the world and the demand for communication. This project aims to address the issue by proposing an alternative method for communication via visible light. It demonstrated that such a system is not only theoretically provable but also practically achievable. This is shown with a system built that will be investigated in the following sections. The system-level requirements define the boundaries for the general operation to meet the project needs. While these requirements may be subject to changes, they can be listed as such:

1. The photograph taken should be compressed and modified to a simpler version such that its transfer is achievable within 2 minutes.
2. The captured image must be parsed into at least 5 packages with a maximum size of 10KB.
3. Data transfer must be robust to environmental lighting conditions.
4. Data should be transferred with a minimum error rate at a minimum distance of 5cm.
5. Operating frequency for data transfer should be above 250 Bytes per second to satisfy the minimum image transfer size of 7.5 KByte, under the assumption that it takes the Shuttle 60 seconds to commute between terminals and perform the handshake protocol.
6. Errors due to data transfer should be minimized such that the information the image contains, i.e. a person, is still recognizable.
7. The overall system contains necessary communication protocols to transfer data and transition between operating modes (states).
8. Subsystems check communication path integrity via a handshake method before data transfer.
9. All subsystems must be capable of storing data.
10. All subsystems must contain their own power unit to operate.
11. Subsystems must be provided with proper housing to deter external hazards.

The distribution of the corresponding requirements in subsystem level is investigated in Table 1 for convenience.

Table 1: *Representation of Requirements in Subsystem Level*

Requirement	**Regarding Subsystem(s)**
1	Terminal A
2	Terminal A
3	Analog Circuitry
4	Analog Circuitry, Shuttle
5	Analog Circuitry, Shuttle
6	Analog Circuitry, Terminal B
7	Overall System
8	Overall System
9	Overall System
10	Overall System
11	Overall System

3. Solution

This project offers a communication mechanism for remote terminals via a Shuttle that acts as a cargo delivery system. The demonstration for showing system capability is to capture an image in one terminal, and display it in another while performing the data transmission over the Shuttle. The overall block diagram given in Figure 1 shows three important subsystems that connect to each other via a fourth subsystem that is one of the main outcomes of this project. These subsystems are : Analog Circuitry(Transmitting Beacon (TB)), Terminal A, Shuttle and Terminal B. Proposed solutions are defined in broader concepts rather than pointing specific method to accomplish; i.e., the main controller logic of the system can be implemented in any programming language, or even in a special digital hardware design. Flexibility is an important merit of the project as complete integration requires multiple iterations of trial and error. One specific solution proposed, however, is the communication method. This is because not everything can be very flexible and some ground-work must be available to make the proposed solution solid. Subsystem solutions give in-depth explanation of the modules briefly described in the overall system.

3.1. Overall System

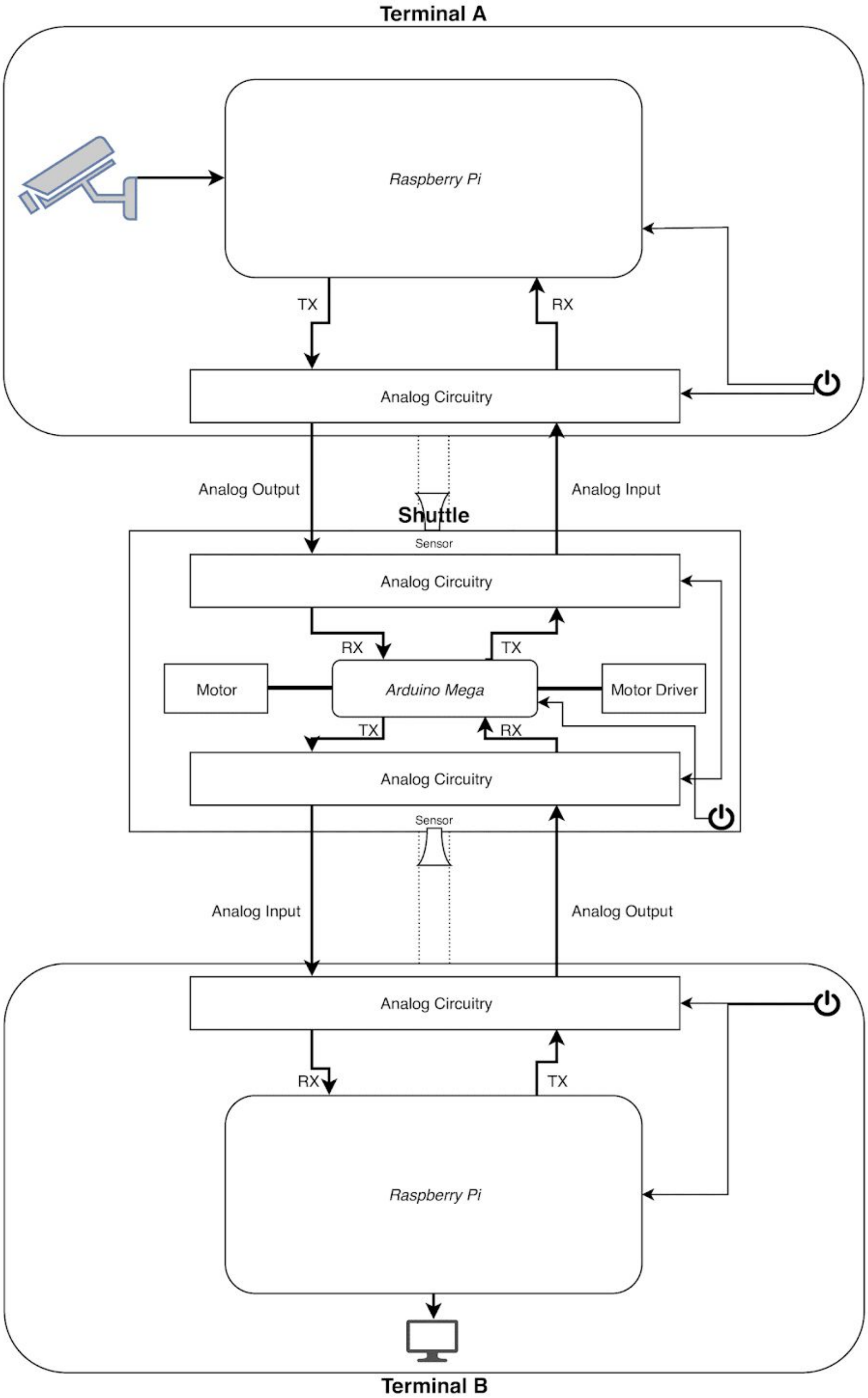


Figure 1: Overall block diagram of the system.

The overall block diagram of the system is given in Figure 1. The system consists of 4 subsystems: Transmitting Beacon (TB), Terminal A, Shuttle and Terminal B. Three subsystems, Terminal A, Shuttle and Terminal B, can communicate only via the Transmitting Beacon(Optical Wireless Communication unit shown as “Analog Circuitry” in the block diagram) embedded in them, which is described in subsystem level definitions given in *Section 3.2*. Each unit has its own power source; hence, all devices are galvanically isolated. This prevents electrical accidents in one subsystem from affecting the others. The base communication method used is the Universal Asynchronous Receive/Transmit (UART) serial communication protocol. UART is a wide-spread, easy to use, robust communication protocol that is used in many electronics that needs to be cheap and communicate with the outside world. As a serial communication method UART can be simply defined as follows. UART can transfer data in sizes of 5 to 9 bits at a time. The system understands the start of a transfer with what is called a “start bit”, which is a transition from logical HIGH to LOW at the input pin. Since the system is asynchronous, i.e. a receiver does not share a common clock with the transmitter, the transfer frequency, known as the “Baud Rate”, must be defined a priori. The unit of baud rate is bits per second. Given baud rate, a receiving device starts taking measurements with equal intervals after reading a “start” bit. The number of measurements taken depends on the transfer configuration; the number of data bits (5 to 9 bits), parity bit and the number of stop bits (1 or 2) is also needed to be set at configuration time. A package of data transfer is completed with a/ “stop bit/bits”. The parity bit is an optional method to check data integrity, but it only indicates a data set is wrong and there is no way to recover the correct data with parity information.

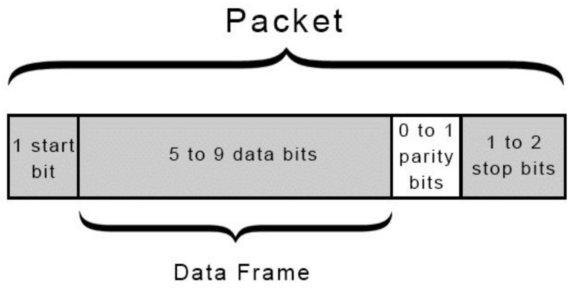


Figure 2: One data packet of the UART

Development boards used in this project (Raspberry Pi 3B, Arduino Mega Pro) are chosen such that they can achieve subsystem level requirements (capturing, processing and displaying an image, storing data, controlling external actuators, etc.), provide the customer with the minimum cost and have UART communication capabilities. This means the system developed is compatible with ANY device that has a UART interface, which is very important since it increases the system lifespan, thus providing a market advantage.

The OWC between two subsystems is achieved via an analog circuitry, named as the “Transmitting Beacon” for beacon is the literal meaning of remote communication via light, which converts the data provided by UART Transmit (Tx) port into visible light and can also capture and digitize ambient information embedded in light and send it to UART Receive(RX) port of the device it is installed on. The conversion method is further explained in the corresponding subsystem definition in *Section 3.2.1*

The actual transfer of data between two terminals is achieved by the “Shuttle” subsystem, which is armed with dual Transmitting Beacons and distance sensors, a high-speed DC motor and an onboard microcontroller for decision making and data storage. Details are also provided in *Section 3.2.3*

Terminals A and B are very similar in hardware implementation as well as software control. These modules achieve data manipulation and image processing. Details can be seen in *Section 3.3.2* and *Section 3.3.4*

3.1.1 Algorithmic State Machine for Main Decision Logic

This section describes the main decision logic to control the OWC system. Many embedded system applications run in an operation mode called “Finite State Machine (FSM)”. An FSM is an abstract machine that can be in exactly one of a finite number of *states* at any given time[1]. An FSM can be modeled using an Algorithmic State Machine (ASM) chart. An ASM chart consists of 3 main elements: States, conditions and conditionals. A state is represented by a rectangular box, it can have multiple input paths and a single output path. The state name is given at the top left corner outside the box, i.e. *S_idle* and the output signals generated at that state are given inside the box, i.e. *take_photo.* Between states, there are boxes called “conditions” and “conditionals”. A condition is represented by a diamond-shaped box, which contains a condition flag that can have a value of either “0” or “1”, where 0 represents “false/no” and “1” represents “true/yes”. A conditional is represented by a rectangular box with rounded edges and it contains condition flag (input) depended output signals; depending on the condition flag, outputs can be generated, the system can directly transition to another state or itself. Figure 3 represents the decision logic for the OWC system in Algorithmic State Machine(ASM) chart format. Using an FSM for the logic decision is critical; because the system is composed of 3 separate subsystems that have their own controller and they need to be working in sync. FSM allows the synchronization easily as state transitions are only allowed under certain conditions and this leaves very little room for errors.

Having made all the necessary definitions in terms of ASM, the operation of the system can easily be described as in Figure 3. The descriptions of input and output signals are provided in Table 2. The system always waits at *S_idle* state checks for the *Start* input signal. Once available, the output signals *take_photo*, *parse_image,* and *set_count* are generated while the system transitions to *S_handshake1* state. This state is used for controlling the Shuttle availability before starting the transmission, which avoids the system from dumping data to unknown targets. *The ready* input signal is triggered by the Shuttle once it is ready to accept data and the system transitions to *S_pickup* state. The total number of packages is kept in a variable *count*. This variable is used with *send_package[count]* output and it determines which data package to transfer during *S_pickup* state. If an error is detected during transmission, the operation is repeated; otherwise, upon successful data transfer, the machine transitions to *S_handshake2* and generates the output *goto_B*. This state is identical to *S_handshake1,* it is only different such that the handshake is done between the Shuttle and Terminal B. In the next state *S_deliver* the package is sent to Terminal B with error control. Upon successful transfer, the system variable *count* is decremented via output *decr_count* and the Shuttle returns to Terminal B via output *goto_A*. The input *Count_0* controls if the transmission is complete. If *true, the* system transitions to the *S_display* state to show the resulting image after which it goes back to the initial state. If *false,* the transmission resumes with the next package until all packages are done.

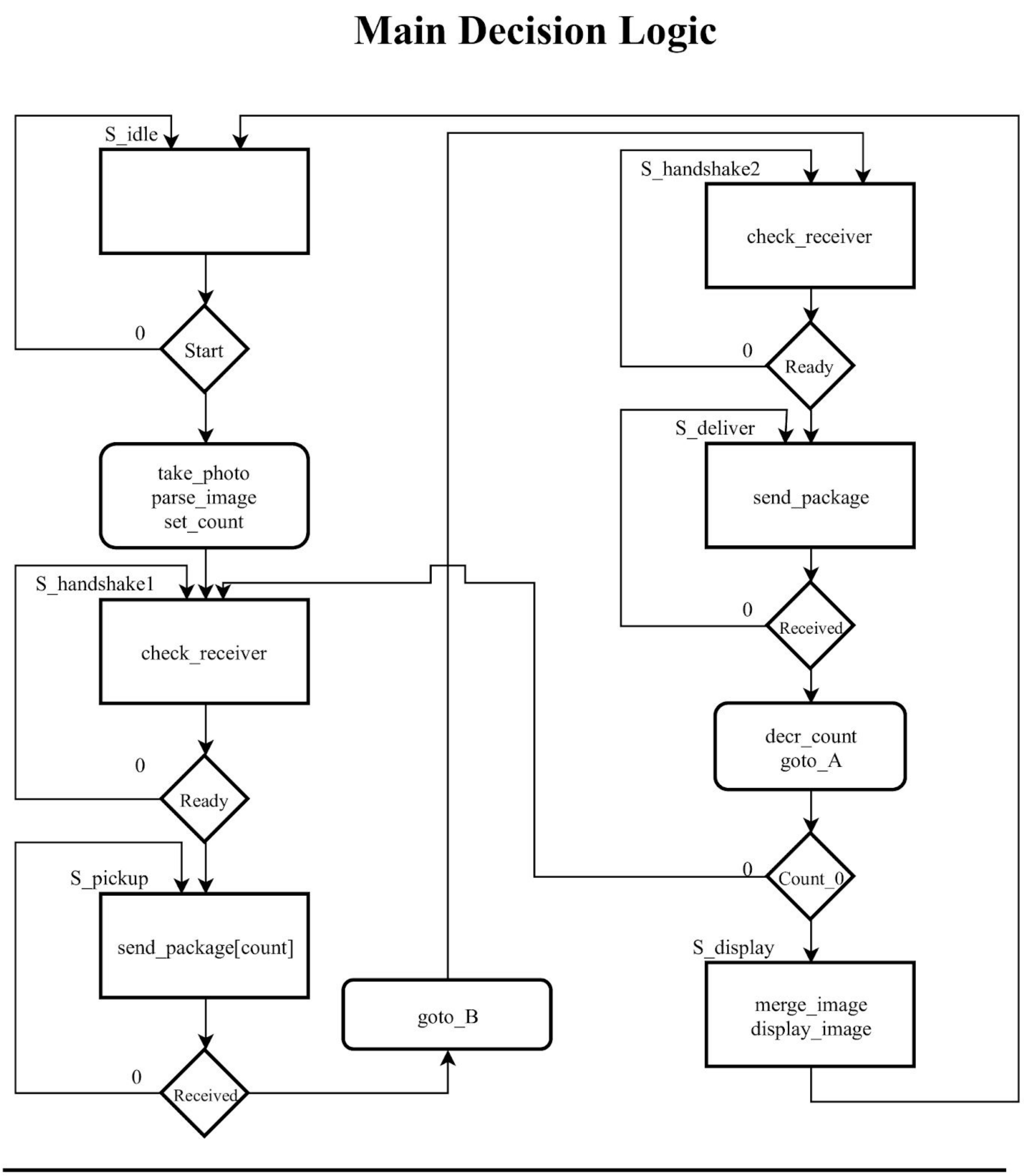


Figure 3: Algorithmic State Machine (ASM) design for main control logic. Square boxes represent states, rounded boxes represent conditional outputs, diamond boxes represent conditions.

***Table 2**: ASM input and output signal descriptions.*

Input Signal	**Description**
Start	External input to start the device.
Ready	A signal generated by receiving a device to start the actual message transfer.
Received	A flag to indicate a successful message transfer. It also acts as a fail-safe error correction mechanism.
Count_0	A flag generated by receiving terminal to terminate delivery upon completion of package delivery.
Output Signal	**Description**
take_photo	Initiates the camera module to capture an image.
parse_image	Initiates software module to divide captured image into packages with size < 10KB.
set_count	Sets a counter to keep track of the image delivery process.
check_receiver	UART polling method to ensure the communication channel is active.
send_package	Transfer of a given data package in byte array format over the UART interface.

goto_B	Signals the transit device to travel from A to B.
decr_count	Signal to propagate the transfer process one step ahead upon successful package delivery.
goto_A:	Signals the transit device to travel from B to A.
merge_image	Signal to concatenate and finalize the received image packages.
display_image	Invoke the display unit to view the received image.

3.2. Subsystems

3.2.1 Analog Circuitry (Transmitting Beacon)

The main purpose of the subsystem is to construct the bridge for the data transfer between the shuttles and terminals. Due to the overall system needing to carry out visible light communication, it has 4 of this circuitry. This subsystem has 2 different capabilities which are basically generating light flux corresponding to the data to be transmitted, and generating meaningful electrical signals corresponding to the received light flux. The data to be transmitted, which is an input of this subsystem, is taken from UART pins of Raspberry Pi or Arduino with dependent on the location of the circuitry. And also, with the dependency on the location of the subsystem, the output of the subsystem is connected to UART pins of Raspberry Pi or Arduino.

The Analog Circuitry must be able to:

1. Transmit digital data provided in 0-5V or 0-3.3V TTL logic levels in the form of the light flux.
2. Receive analog data in the form of the light flux.
3. Filter, amplify, digitize and transmit the received data at 0-5V or 0-3.3V TTL logic levels(as required).
4. Operate on reasonable ambient light conditions, i.e. office lights, sunlight, spotlights that are not directly incident on the viewports.
5. Have a power consumption level < 2Whr for sustainability.

In this subsystem, to generate and capture the visible light, the LEDs, which are 3mm Phototransistor T-1 PT204-6B [4], and Phototransistors, which are 10mm Round Color diffused Red Leds [4], are used. To construct the required amplifier and filter configurations, the NE5532p Op-Amp [3] is chosen within the other alternatives due to the high slew rate and bandwidth to get much more communication data rate.

As can be seen in Figure 4, the subsystem has two distinct parts that ensure the capabilities mentioned before. To start with the generating flux capability, at the beginning of the circuitry, there is the simplest transconductance amplifier as the LED Driver which converts the Tx INPUT voltage to current. After this conversion, the output of the LED Driver is directly connected to the LED to generate VL OUT as visible light.

To continue with the capability of generating meaningful electrical signals, the circuitry gets VL IN as an input. To convert this visible light input, Phototransistor is utilized as mentioned before. The phototransistor is the general-purpose transistor which its base is directly connected to the flux instead of the supply voltage. Whenever flux hits the base, there is a minority carrier generation, and this leads to current. To convert the current to voltage, the Transresistance Amplifier is constructed. After this converted voltage signal is compared with the very small negative voltage to get the square wave. It is compared with the very small negative voltage because this comparison is much safer than comparing it with the 0V in terms of glitching and level shifting. After this comparison, the obtained square wave is directly input to Bandpass Filter. This filter is the multiple feedback filter that has high bandwidth and sharp transition. As can be seen in Figure 5 and 6, it has 3 kHz center frequency and sufficiently sharp frequency response which suppresses the ambient noise, such as 100 Hz bulb light, effectively. After this filtering, this wave lost its square form a bit. So, this filtered wave is subjected to comparison one more time to get the proper square waveform. This final square wave has -5V to 5V or -3.3V or 3.3V corresponding location of the circuit since the Raspberry Pi UART pins work with 0V- 3.3Vand Arduino UART pin work with 0V-5V. To get rid of the negative voltages, there is a Rectifier circuit before the Buffer. The Rectifier circuit consists of a series-connected transistor and resistor. At the end of this subsystem, Rx OUTPUT is directly connected to microcontrollers with proper voltage values.

The preference of selecting center frequency of filter is related with a baud rate of the system. In prototype phase, the baud rate of the system is 9600 bit/sec. This means that the maximum frequency of the transmitted rectangular signal is 4.8 kHz. Based on the experiment, observed frequency range of the transmission is approximately between 2.5kHz and 4 kHz, therefore, the 3 kHz center frequency was determined and implemented.

As can be seen in Figure 7, -5V,5V is used as a supply voltage of this subsystem. Furthermore, which cannot be specified in Figure 7, between almost all block of this subsystem there are DC coupling capacitors and between the negative supply-ground and positive supply -ground there are floating capacitors.

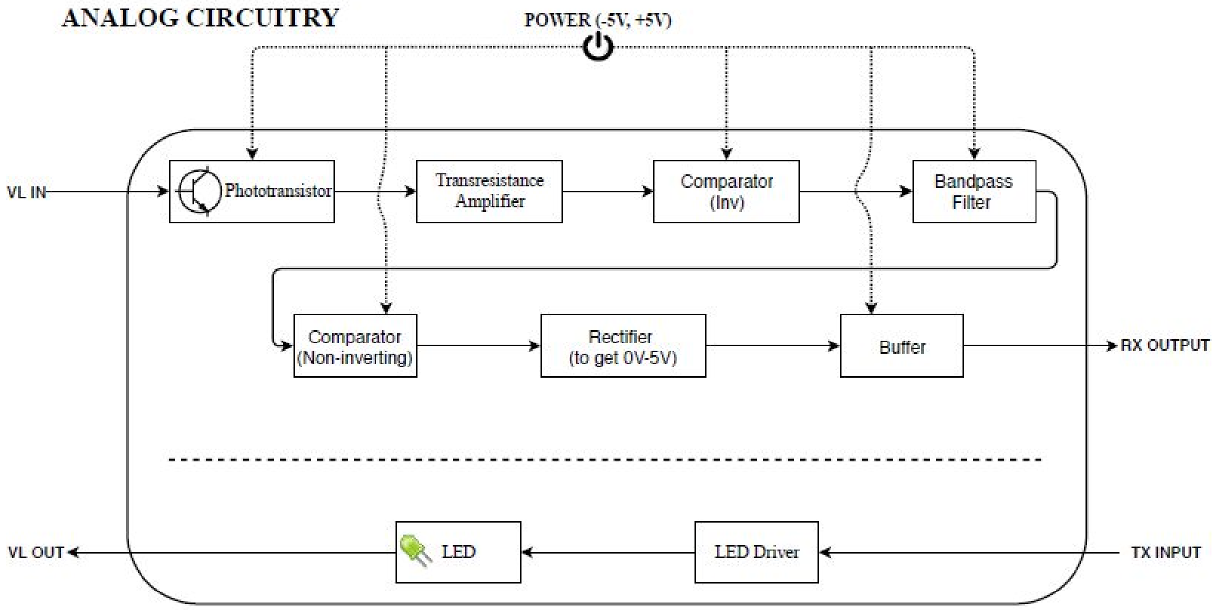
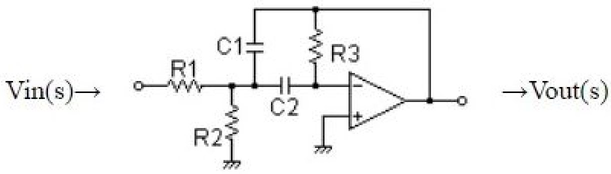


Figure 4: Block diagram of the subsystem of Analog Circuitry

Multiple Feedback Filter



Transfer Function:

$$G(s)=\frac{-73313.782991202s}{s^2+76745.49198228s+355582749.80862}$$

R1 = 6.2kΩ
R2 = 15kΩ
R3 = 6.2kΩ
C1 = 0.0022uF
C2 = 0.047uF

Center frequency

f_0 = 3001.1691510729[Hz]

Figure 5 : Circuit Schematic of the Bandpass Filter

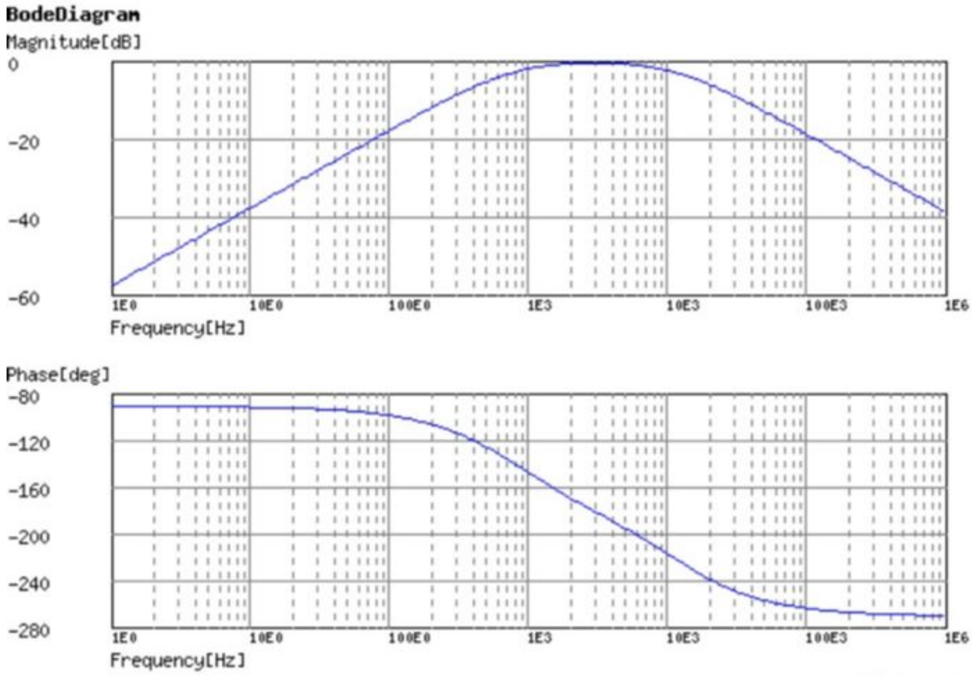


Figure 6: Bode diagram of the Bandpass Filter

Source Voltage Generation from +12v to +5V/-5V

At the current configuration, a power module is required to operate the Analog Circuitry subsystem. To obtain from the positive voltages to negative voltages, after a detailed literature searching, using the Ćuk converter topology [2] is determined.

A quite unique topology was named after Mr. Slobodan Ćuk who first presented the design. It is a topology which generates a negative output voltage from a positive input voltage. This topology does not require a transformer. While two inductors are necessary, they can be dual windings on a single core. Also a coupling capacitor in the power path is needed.

Figure 7 shows a Ćuk topology. For implementation of this circuit, a switching regulator or controller with a negative feedback voltage path is needed. Very few modern integrated DC to DC converter devices offer such a negative feedback pin. Certainly devices with a positive feedback pin may also be used as long as a discrete voltage inverter is added to the feedback path. This additional operational amplifier increases system cost but it also adds multiple components in the sensitive feedback path which often yield output voltage accuracy problems and may easily couple system noise into the feedback loop yielding noise on the output voltage.

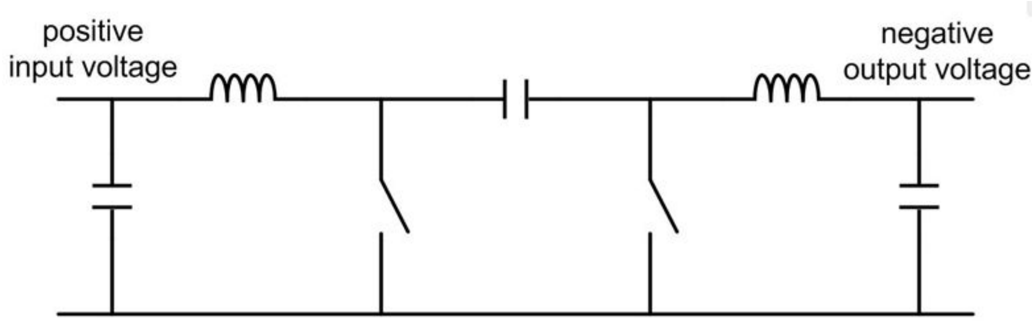


Figure 7: Ćuk topology generating a negative voltage from a positive supply

Generally, the Ćuk topology is very low noise. This comes from the fact that there is an inductor on the input side as well as on the output side. Current flow through an inductor cannot change instantaneously, thus input currents and output currents are very stable currents opposed to other switching regulator topologies.

3.2.2 Terminal A (Transmitter)

Terminal A captures the image at the beginning and decomposes it into chunks. Also, it communicates with the shuttle via Universal Asynchronous Receiver/Transmitter (UART) communication and transmits the chunks respectively with the LEDs.

Terminal A must be able to:

1. Capture and store an image.
2. Process the image for necessary size reductions, divide it into packages of maximum size 10KB, and store them as serial-transferable files for OWC.
3. Drive the TB module with necessary power rails (i.e. 0-5V).
4. Read/write messages over the TB for data transfer, handshake, state transition, etc.

The overall process begins with the capturing of the image via Raspberry Pi Camera v1.3. This can be done either by pushing a button or saying “cheese”. By using the built-in functions of the Raspberry Pi Camera, the image will be taken with determined resolution. To code the whole process, Python language will be used because it is more user-friendly and it has a very rich library. After the image was taken, it will be compressed and divided into equally sized chunks. The size of these chunks will be less than 10KB i.e., within the restrictions. According to the set counter, these chunks will be sent via the Tx pin of the Raspberry Pi. Also, the Raspberry at the transmitter terminal must know when it will start to send the first chunk. Therefore shuttle must communicate via Rx pin of the Raspberry. In order to use UART communication via Rx-Tx pins of the Raspberry Pi, Serial Read and Serial Write codes will be used. Block diagram of Terminal A can be seen in Figure 8.

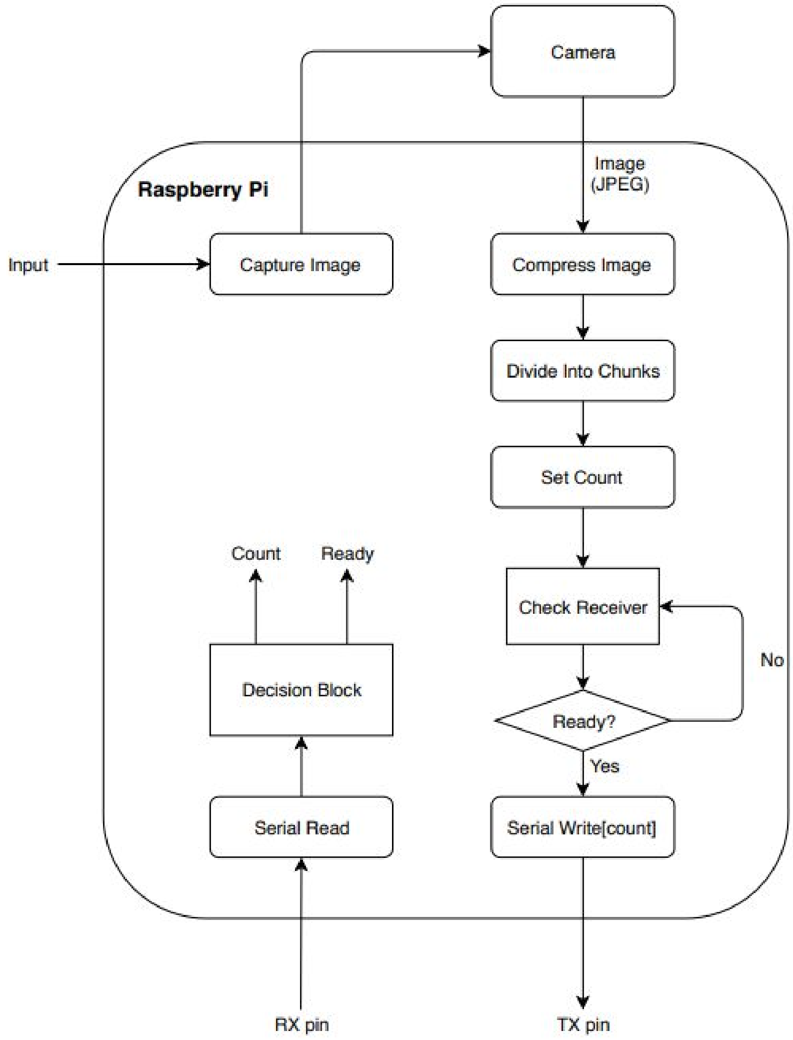


Figure 8: Block diagram of the Terminal A

3.2.3 Shuttle

As stated earlier, the main task of the project is to carry a number of packets between two terminals that are 1.5m apart from each other. Hence the LEDs that are going to be used in this project are not suitable for the direct data transmission between terminals, a mobile vehicle will be included as a transportation medium. The main services of this vehicle are to load a data packet originated from the first terminal, travel along with a physical guide and dispatch the data to the second terminal.

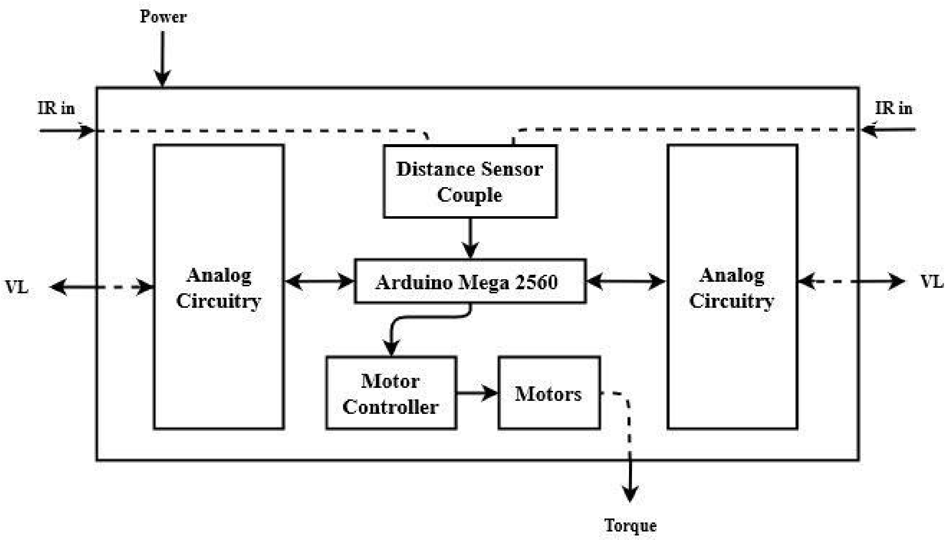


Figure 9: Functional diagram of the Shuttle

The Shuttle must be able to:

1. Communicate over the TB for data transfer, handshake, state transition, etc.
2. Drive 2 TB modules for data transmission/reception to both terminals.
3. Store data to non-volatile memory(memory type that stores the data even if the power is down) to preserve data even if a power outage occurs.
4. Travel at a speed of 0.4 m/s, under the assumption that the travel length is 1.5 meters and the Shuttle can travel a distance of 20 meters in 60 seconds (during which it can carry up 6 packages).
5. Sense distance along travel axes between terminals.
6. Control the motor output according to the distance readings to correctly align subsystems before initializing data transmission/reception.

The functional diagram of the Shuttle is provided in Figure 9. The data transfer between the shuttle and the terminals is done through Analog Circuitry whose I/O parameters are modeled as Visible Light, VL. Refer to *Section 3.2.1* for further specifications and details. Between two consecutive loading and dispatching the corresponding data packet, the shuttle is to travel from one terminal to the other in order to take part in the data transmission. The travel mechanism is composed of two DC motors and a control unit which is supported with distance measurement instruments so that the controlling algorithm is able to adjust the position of the shuttle before any data transmission occurs. Referring to Figure 9, the input signal to the DC controller unit is demonstrated as IR_{in}.

The shuttle is mainly composed of ***a voltage regulator unit*** to provide several blocks with appropriate reference voltages and for several initializations, ***two analog circuitry*** for data transmission between the shuttle and terminals and for handshake protocols, ***a memory unit*** to store the received data packet, ***a DC motor control unit*** to regulate the travelling mechanism. A fully expanded block diagram for the Shuttle can be seen in Figure 10.

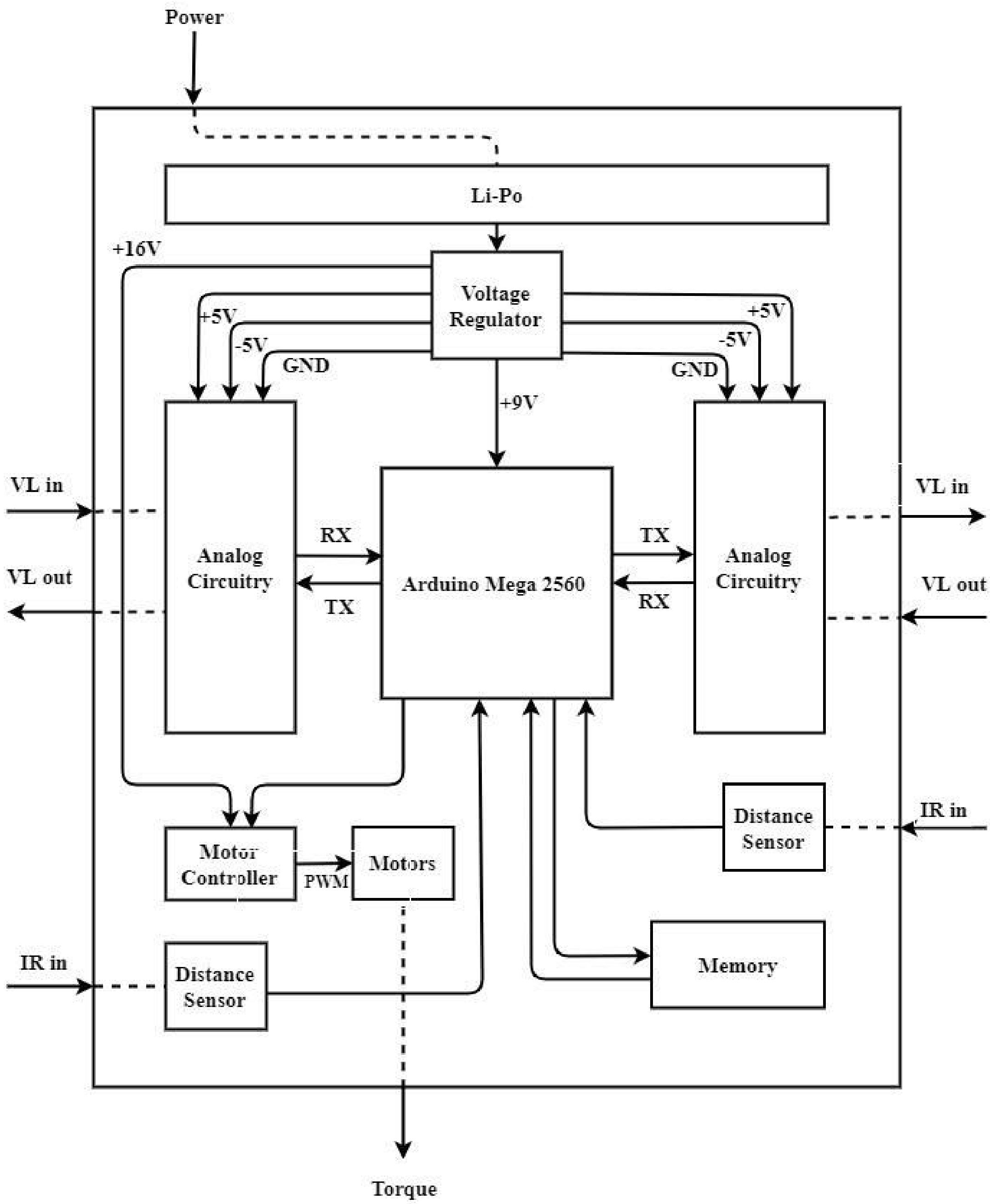


Figure 10: Detailed functional diagram of the Shuttle

Voltage Regulator Unit

The conversion of +12V to the several other reference voltages that are going to be used in the remaining parts of the shuttle is done in this unit. It is composed of step-down regulators, step-up regulators, and charge-pump regulators in order to decrease the output reference voltage to a smaller value, boost the output voltage to greater value and invert the output reference voltage respectively. The corresponding conversion rates are as follows:

- **+12V** to **+5V/GND/-5V** for Analog Circuit modules. (Refer to *Section 3.2.1* for details)
- **+12V** to **+9V** for Microcontroller

- **+12V** to **+16V** for DC motor controller

Analog Circuit Modules

The shuttle installs two sets of analog circuitry for data transmission and for the handshake operations that will synchronize the data transmission between shuttle and terminals. Please refer to *Section 3.2.1* for several specifications and details about the operation principles of the analog circuitry.

Memory Unit

The received data packet will be stored in a non-volatile(not requiring power to store data) memory unit (an SD card) throughout the data transportation from the first terminal to the second terminal. After completing one cycle, that is, when the data is transmitted to the secondary terminal, the memory will be erased to meet the specification of carrying one package at a time.

DC Motor Control Unit

The motor control unit consists of a set of distance sensors, a microcontroller, a DC motor controller and a set of DC motors. DC motor controller is included in between the microcontroller and the motors because the DC motors require a greater current sink than the maximum value that the microcontroller is able to provide.

Distance Sensors

GP2Y0A21YK0F Sharp sensors are chosen as our distance measurement instruments since they are capable of providing a significant voltage difference as the distance is varied. The voltage decrement per centimeter is 125 mV/cm when the measured distance is varied from 7 cm to 20 cm, which provides us with a conveniently steep distance measurement.

Microcontroller

The microcontroller is the main device to control the processes in the shuttle. Apart from managing data storage, it produces PWM enable signals for the DC Motor controller to regulate the shuttle movement. The duty cycle of the produced PWM enable signal is determined according to the measured distance value as demonstrated in Figure 11.

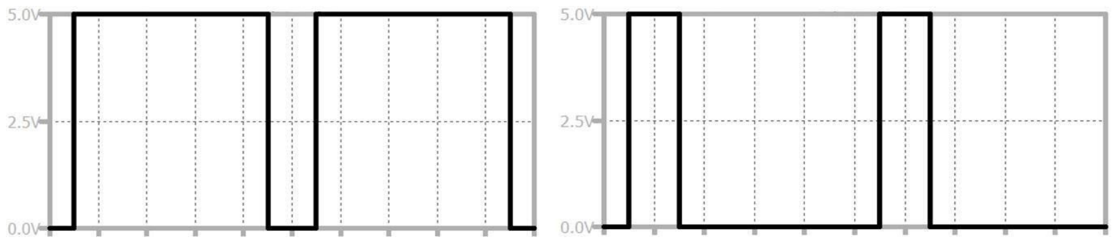


Figure 11: PWM enable output of Microcontroller when the measured distance is 60cm and 20cm respectively

DC Motor Controller

DC motor controller serves as a bridge between Microcontroller and the DC motors. Hence it is supplied directly with the voltage regulator, it can provide DC motors with sufficient current.

DC Motors

Two sets of DC motors are installed in the shuttle to generate appropriate torque for travelling. It is possible to categorize the travelling distance into three; namely, start-band, free-band and stop-band where the generated torque in the DC motors are constant in the free-band whereas it increases/decreases linearly in the start/stop-band. Such torque generation in the DC motors are attained by adjusting the duty cycle of the generated PWM signal in the microcontroller in accordance with the measured distance. Therefore, a soft start - soft stop mechanism is accomplished.

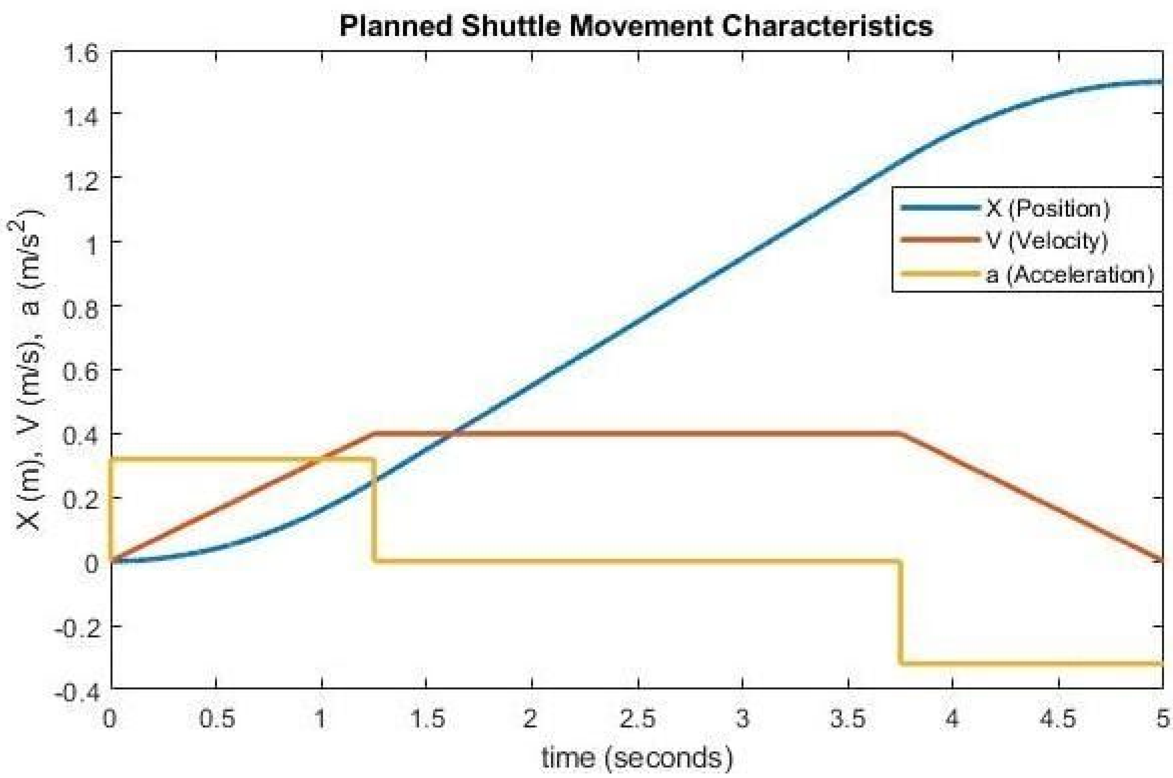


Figure 12: Desired shuttle movement characteristics

The travelling velocity of the shuttle is specified to be 0.4m/s so that there is enough time left for overall data transmission under two minutes. Assuming that this value is valid only for the free-band, the required movement characteristics is provided in Figure 12 when the duration of a single travel is adjusted to 5s.

The movement characteristic that is provided in Figure 12 can be accomplished with a control mechanism that installs three distinct algorithms. When the measured distance is in the start-band, the duty cycle of the controlling signal increases gradually, which can be accomplished with a closed-loop control configuration. When the measured distance is in the free-band, the duty cycle of the controlling signal is setted to its maximum, letting the shuttle to be controlled simply with an open-loop configuration. However, the controller configuration is switched back to closed-loop when the measured distance is in the stop band, making it possible to decrease the speed of the shuttle gradually. The designed piecewise conditional closed loop control configuration is illustrated in Figure 13 for convenience. *Ref*, *Y*, *U* and *M* correspond to reference signal, the distance of the shuttle from the destination terminal, controlling signal and the measured distance respectively. The dashed lines link the corresponding blocks to each other conditionally according to the measured distance (*M*). That is, when the measured distance is in the free-band; the closing branch *M* is disconnected from the loop and the according controlling signal is selected in *U*, turning the overall controlling mechanism into open-loop. On the other hand; when the measured distance is either in the start-band or in stop-band, the closing branch *M* is connected and again the according controlling signal is selected in *U*, turning the overall controlling mechanism into a closed-loop configuration.

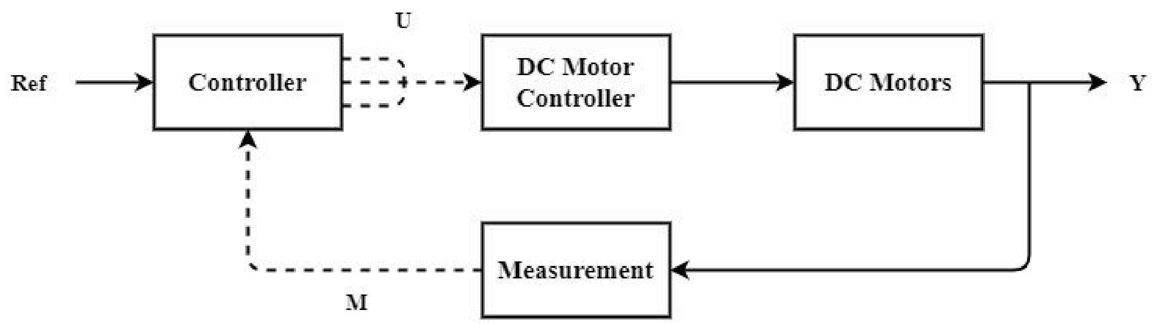


Figure 13: Desired shuttle movement characteristics

In order to achieve the movement characteristics that is demonstrated in Figure 12, the chosen DC motors should have a certain minimum torque capability. This value is calculated in Eq (1) by using the desired acceleration rate in Figure 12.

$$\begin{aligned} T_{min} &= J * a = (\tfrac{1}{2} * m * r^2)(2\pi * \tfrac{rpm}{60} * \tfrac{1}{\Delta t}) \\ &= (\tfrac{1}{2} * 0.35 * 2.5^2)(2\pi * \tfrac{150}{60} * \tfrac{1}{1.25}) \\ &= 13.74\ kg/cm \end{aligned} \tag{1}$$

Note that; m, r and rpm in Equation 1 corresponds to the total weight of the shuttle, the radius of the wheel and the rotation per minute values of the system. Henceforth, Namiki-22CL-3501PG12V is a suitable choice for this project, since its stop torque rate is 16 kg/cm. Moreover, its current sink value is sufficiently low as it will be examined in detail in *Section 3.5*.

3.2.4 Terminal B (Receiver)

Terminal B is the terminal where the project finalizes and we become graduates. One can say that it’s mission is very critical.

In Terminal B analog circuitry is two-sided likewise in the analog circuitry in Terminal A. Which means that it is able to both receive data from the shuttle and transmit data to the shuttle. This is required for the handshake protocol, which ensures safer transmission of data.

Terminal B must be able to:

1. Read/write messages over the TB for data transfer, handshake, state transition, etc.
2. Process the data packages for image retrieval.
3. Display the retrieved image
4. Drive the TB module with necessary power rails (i.e. 0-5V).

First of all, data that the shuttle carries will be collected by the analog circuitry dual to the one in the source terminal. Output will be connected to the Rx pin of Raspberry Pi which enables the UART and using Serial Read algorithms, data will be saved. Since we are using the safe transmission technique of UART, preamble of the transmitted signal does not have to be very long for the system to understand the transmission is started and ended.

Data that we saved needs to be separated from the preamble signal before reconstruction. Since there will be more than one data packages, saved data also needs to be ordered for a correct reconstruction. After receivement of the packet is done, Terminal B needs to know if the whole image packets are transferred or not. This can be achieved by fixing the packet count or adding a different but also known preamble at the end or the beginning of the last package. If it is not done yet, it needs to tell the shuttle to “go for another round”. These correspond to the basics of the handshake in Terminal B. If whole packets are received Terminal B reconstructs the transmitted data packages into an image.

Another thing to keep in mind is the losses in the system may cause reconstruction to be impossible since even a small number of data loss in the system will disarray the image data and not matching data array lengths makes these processes impossible. To overcome this problem, error detection and correction methods should be taken into consideration. Detection by itself is not enough, errors need to be corrected. A few possible algorithm implementations can be listed as

- Backward error correction: Once the error is discovered, the receiver requests the sender to retransmit the entire data unit.
- Forward error correction: In this case, the receiver uses the error-correcting code which automatically corrects the errors.

Process time will be approximately equal to the process in the source terminal with the exception of the error correction. The recorded image can be shown on the monitor when the whole process is done, as a whole, or after each round reconstructing it fragmentarily.

3.3. Test Procedures, Experiments, and Results

Tests that have been implemented up until this stage of development in the project are presented in this section, including the steps for tests and their results.

3.3.1 Test Procedure for Transmission Error Rate

The transmission error rate test measures the number of erroneous readings over a data set of 1000 Bytes. As of now, it takes the Transmitting Beacon 1s to transfer 1KB of raw data. This device consists of two parts, a transmitter, and a receiver. These parts will be placed at a distance of 10 cm. The setup will be placed on a measuring paper for easier distance reading.

1. The test will be conducted using two Arduino Uno. These devices will feed/capture the digital test signals to/from analog circuits.
2. The inputs and outputs of the system will be observed via the serial terminal application Termite running on a test laptop.
3. The distance between the transmitter and receiver will be varied under no fluorescent light condition and the changes in the error rate will be observed in the serial terminal.
4. The distance between the transmitter and receiver will be varied with the fluorescent light condition and the changes in the error rate will be observed in the serial terminal.

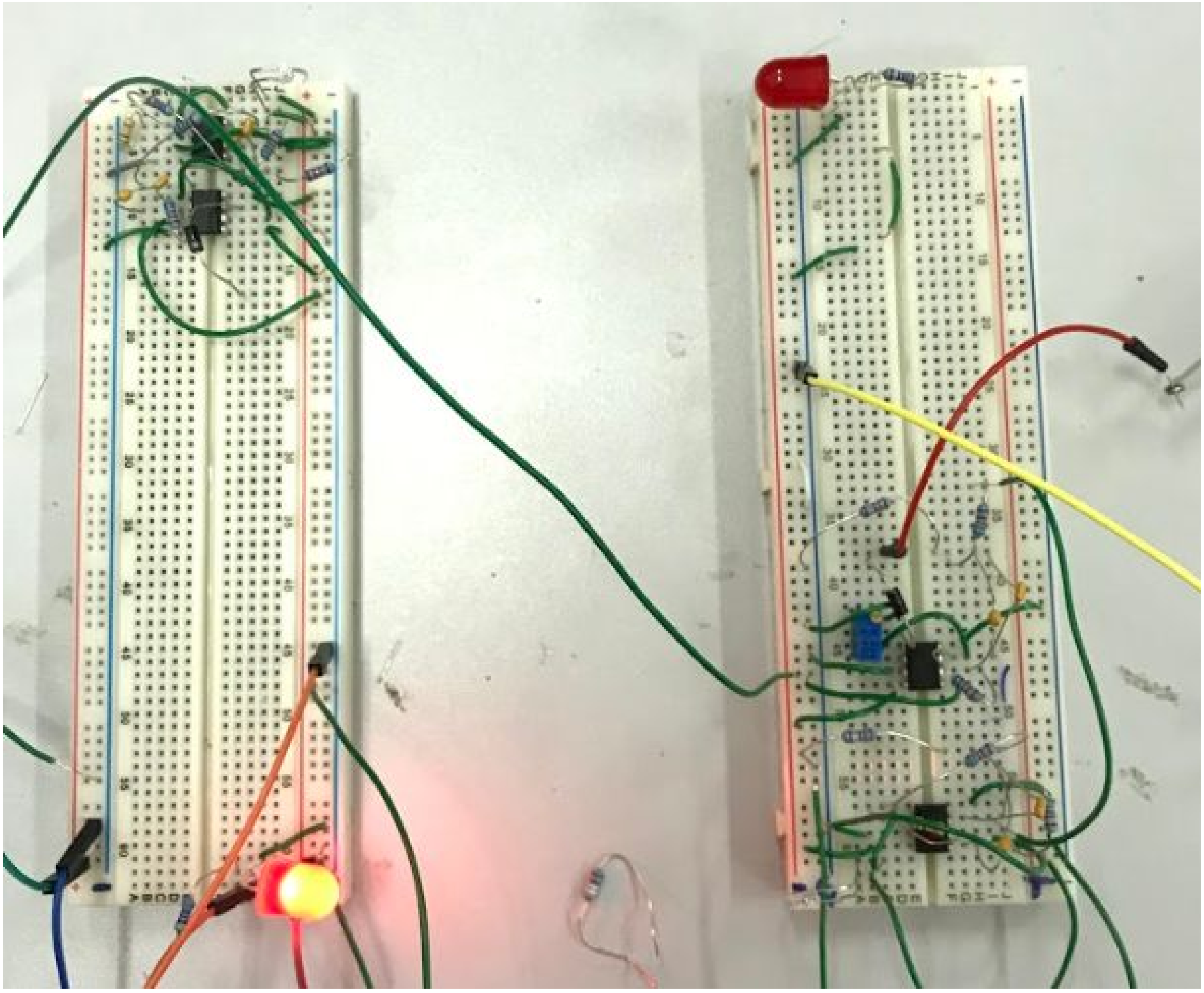


Figure 14 : Analog Circuitry

Results

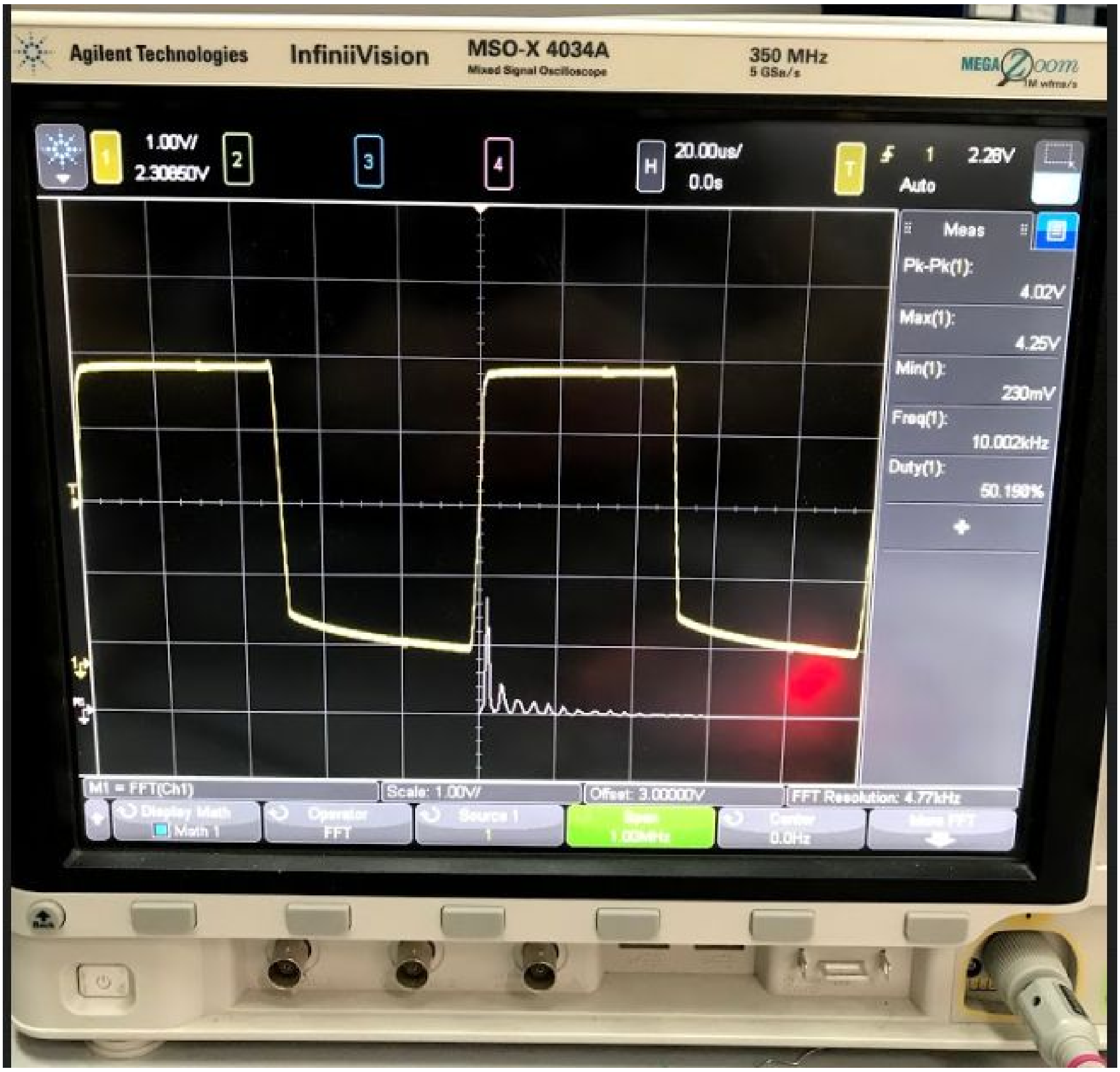


Figure 15: Oscilloscope view of the analog output with distance around 10 cm

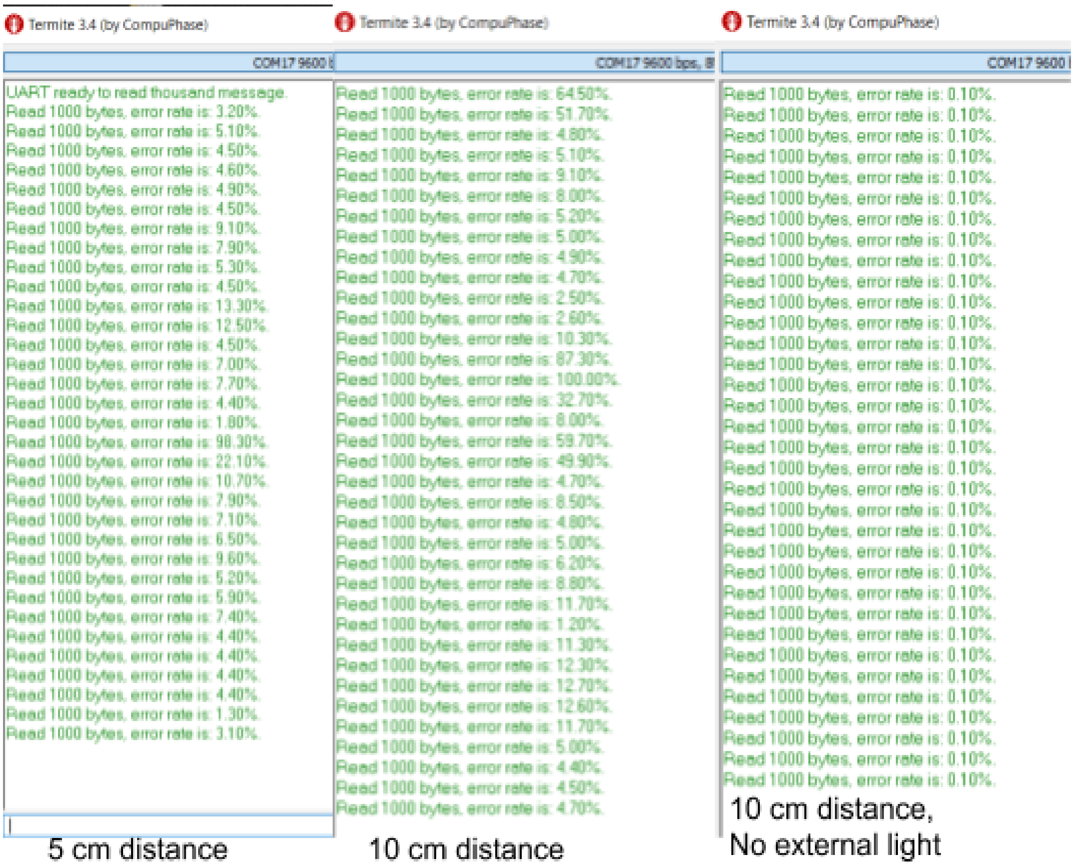


Figure 16: Termite program outputs for various combinations of error rate test.

As it can be seen in Figure 16 columns 1 and 2, in the presence of an external light source(in this test a fluorescent lamp) the transmission error rate increases with increasing distance. On the other hand, provided that the system is rejecting external noise sources, the error rate falls to 0.1% as in column 3. This is the desired state of operation for our device.

3.3.2 Test Procedure for Shuttle Commutation

The Shuttle rides on a guiding bar to decrease the translational motion complexity into one dimension. This also ensures viewport alignment for TB devices, which minimizes transmission errors.

1. The carriage will be placed on the guiding bar that leads to an artificial terminal.
2. The device will be manually started by switching on the power.
3. The embedded algorithm for soft start-stop will demonstrate the commutation capability.
4. The device will be turned off.

Results

The Shuttle is capable of controlling its speed using the feedback from laser distance measurements. It reaches up to 0.4m/s.

3.3.3 Test Procedure for Image Processing and Transmission

In order to demonstrate UART communication of the Raspberry Pi's, the following test has been done.

1. UART pins of the two Raspberry Pi's were opened to the serial communication.
2. Tx pin of the first Raspberry connected to the Rx pin of the other Raspberry as well as for the Rx-Tx connection via cables.
3. Counter data sent from the first Raspberry(Transmitter) by using Serial Write code and read from the second Raspberry(Receiver) by using Serial Read code.

Result

The counter which increases a value of 1 in a second was read at the receiver side and UART communication between two Raspberry Pi's are successfully completed.

3.4. Alternative Solutions and System - Subsystem Level Risk Assessment

Even in a well-prepared system, because of the external and unnoticed internal reasons, lots of errors may arise. To overcome the effects of these errors, limitations, and disturbances introduced to the system should be forecasted before they affect the system.

One, and the main reason for the error in the project is the highly environment-dependent visible light communication (VLC) medium. VLC is not a fully stable data transfer system by itself since its success depends on the external conditions of the environment. This variable success of the VLC channel obligates us to make provision for possible failures of the project.

Error in the VLC causes data loss or wrong data transmission, and both of these are very critical errors that can cause complete failure of the project if any precaution is not taken. Reconstruction of the image in the final step highly depends on the correctness of the transmitted data all the way through Terminal A to Terminal B.

Designing a system with multiple subsystems is a hard task when it comes to integration and it is always useful to have alternative solutions. Alternatives provide a frame of reference to compare the quality of the current solution. They can also improve the solutions by adding new methods. Table *3* shows an alternative proposed for subsystems and algorithms currently used in the conceptual design.

Table 3*: Present solutions and their alternatives*

Present Solution	**Alternative**
Transmitting Beacon Consists of cascaded filters and amplifiers, takes UART packages as input and produces UART packages as output in the form of digital signal or visible light. This simplifies	Instead of directly using UART signals, a carrier AC signal can be used. Use of such a signal helps to shift the operating frequency of the system to a level where noise to signal ratio is lower. The methods in the literature

the data transfer and decreases computational overhead.	are called Amplitude Modulation (AM) and Frequency Modulation (FM). The both are analog modulations type and required tedious design techniques. The complexity of the implementation is the main drawback of this solutions. Rather than choosing this difficult path, preferring UART is much more feasible. Another bottleneck is related with the power consumption of the analog circuitry. Based on hand calculations and simulation results can show an increase in power consumption of 50 percent.
Terminal A Consists of Raspberry Pi 3(RP3) and its camera module as well as the TB module. RP3 is very sufficient for handling basic computer tasks such as file manipulation. One other major advantage is that it runs on Linux, the open source operating system, which is very useful in software development.	There are not many competitors to RP3 when it comes to price. However, a recent board developed by NVIDIA, the Nano board, is being utilized in AI applications. It is available for 100$ whereas RP3 costs 35$.
Shuttle Consists of a differential drive car mounted on a guiding shaft, Arduino Mega Pro microcontroller, IR distance sensors and two TB modules as well as DC motor and motor driver IC. Arduino Mega is chosen for its large peripheral capability(multiple UARTS) and small surface area.	There are many alternatives when it comes to microcontrollers, but Arduino series boards are always easier to integrate due to its libraries for interfacing hardware. Alternatively, we can use a board from ST Electronics or Texas Instruments with similar specifications. The pricing for all three brands is very close.
Analog Filters Consists of a single stage wide bandwidth and sufficiently sharp transition Multiple Feedback bandpass filter. The weak points are not very good to prevent ambient noise between 1kHz to 20 kHz.	Instead of using single band pass filter, trying to use a single band notch which eliminates 100 Hz noise and a high pass filter which eliminates the other high frequency noises.Also instead of using single-stage Multiple Feedback bandpass filter, double or triple-stage filter configuration can be preferred. Different from the analog solution, the digital filter configurations can be considered as a solution.
Terminal B Consists of Raspberry Pi 3(RP3) and the TB module. This terminal is also plugged into an external monitor. RP3 is very sufficient	There are not many competitors to RP3 when it comes to price. However, a recent board developed by NVIDIA, the Nano board, is

for handling basic computer tasks such as file manipulation. One other major advantage is that it runs on Linux, the open source operating system, which is very useful in software development.	being utilized in AI applications. It is available for 100$ whereas RP3 costs 35$.
Main Decision Logic Proposes a closed loop Finite State Machine implementation for OWC system. FSMs are expandable and easy to debug. They provide a framework rather than hard coded implementation; any programming language(C, C++, Python) can be used to implement it.	A free running system that executes tasks as they arrive. This type of implementation is useful for systems where range of tasks assigned are either very large or can increase/decrease at runtime. Such an implementation is not very useful for our system, but can be implemented if needed.

3.5. Technical Specifications

- **Dimensions**

As mentioned in Section *3.2.3*, the shuttle is composed of a power unit including a Li-Po battery, several voltage regulators, DC Motor control unit and a microcontroller. The overall weight of the design is 0.7kg and the instruments of the shuttle are placed on a 15cm wide and 20cm long platform.

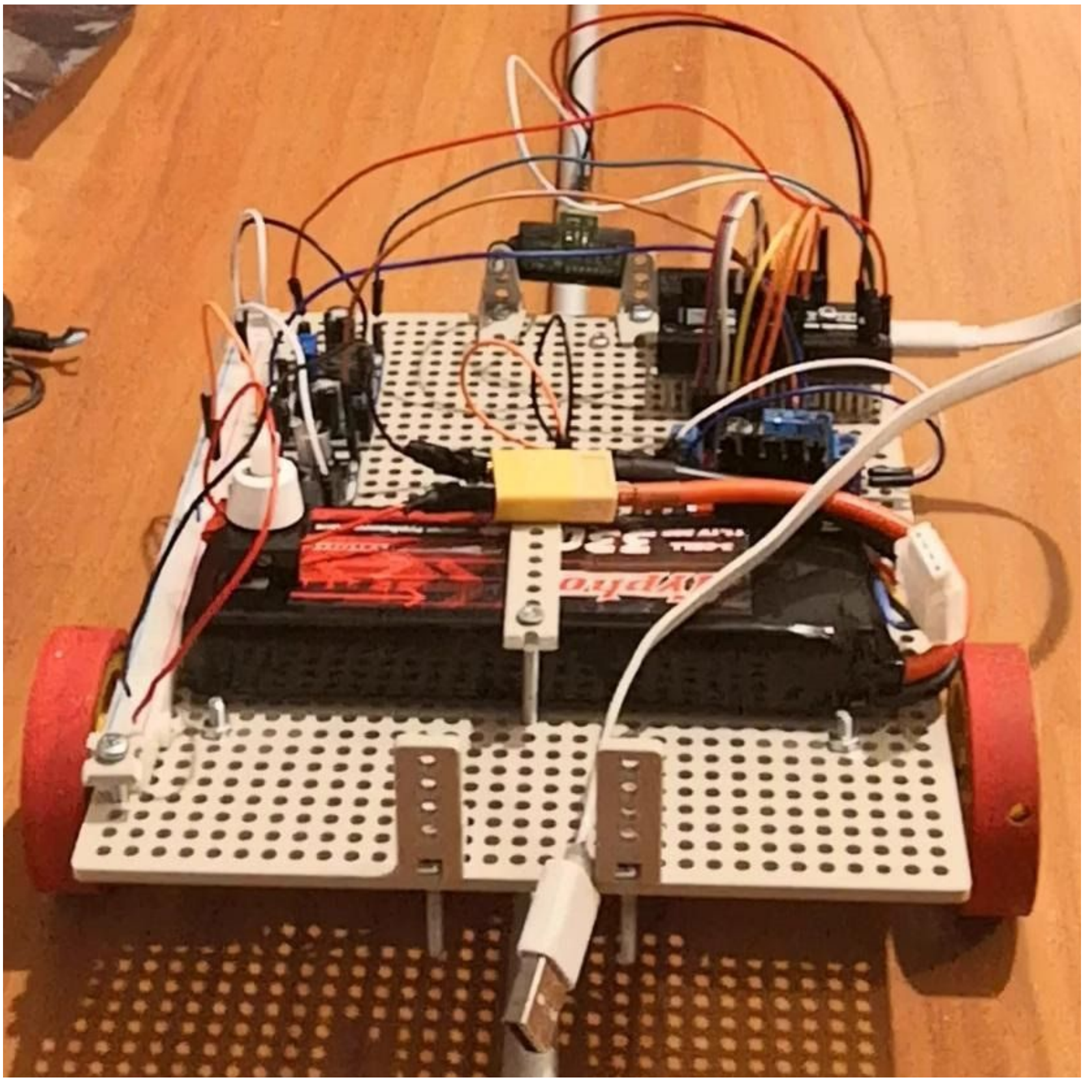


Figure 17: The design of the shuttle

- **Power Consumption**

Device	Average Power Consumption
Microcontroller	15 mA
Voltage Regulators (total)	200 mA
DC Motor Controller	50 mA
Distance Sensors (total)	30 mA
DC Motors (total)	400 mA
Total	695 mA

The overall operation life-span is calculated in Equation (2)

$$t = \frac{battery\ capacity}{P_{total}}$$

$$= \frac{3300\ mAh}{695\ mA} = 4.74\ hours \qquad (2)$$

Figure 18 represents terminals A and B with a guiding track between them. This visual is obtained using 3D Computer Aided Drawing tool Autodesk Fusion 360. The dimensions of the terminals are arbitrary; however, for the sake of simplicity, they are in range with the dimensions of the Shuttle.

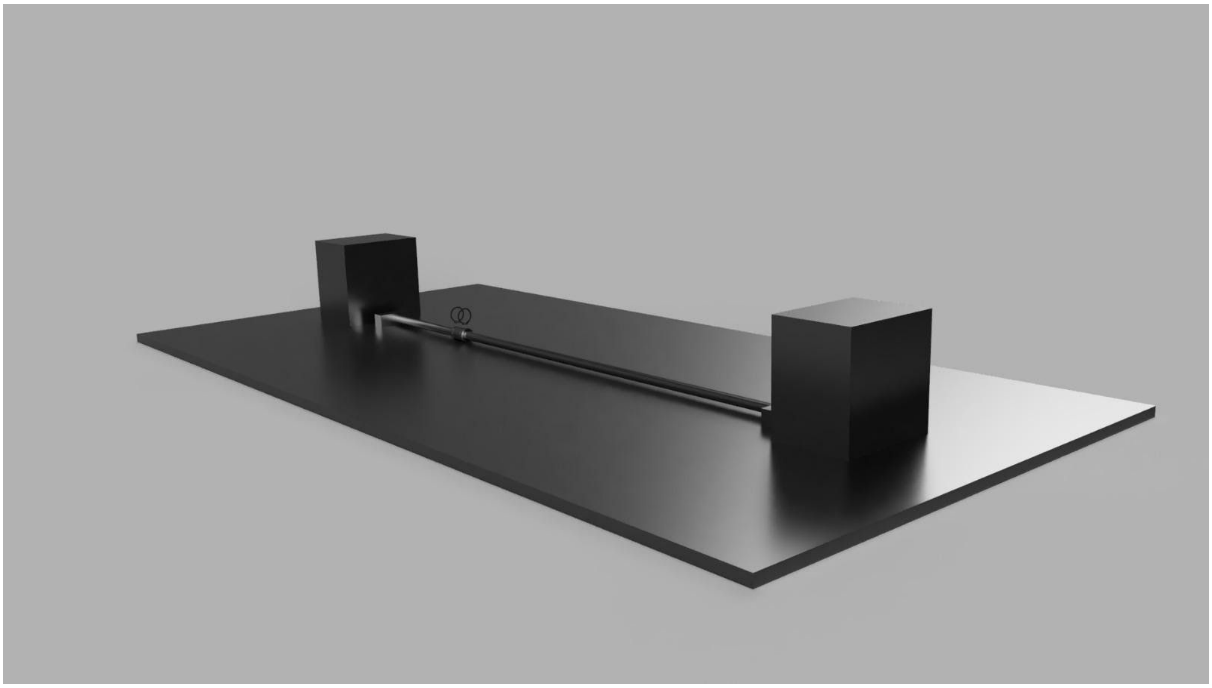


Figure 18: Conceptual representation of terminals and guiding bar.

4. Plans

4.1. Detailed Breakdown of Planned Work

National Electronics & Semiconductor Technologies (NESET) Company was founded by highly motivated Electrical & Electronics Engineering students to provide our nation with the cutting edge technologies. Our team consists of people from various fields and work experiences to provide a diverse thinking and problem-solving environment. Also, see *Table 4* for the respective workload of the team members up to conceptual design.

- Y. Emre İKİZ worked on communication protocols and implemented the test methods on microcontroller.
- Ö. Can KARAMAN worked on analog circuitry design like transresistance amplifier design, filter design, etc.
- Rafet KAVAK worked on capturing image and compressing it at the transmitter side by using Raspberry Pi.
- Ersin KESKİN worked on the mechanical design of the shuttle.

- Ayşegül KILIÇ worked on image composition and decomposition methods by using Raspberry Pi.

Table 4: Respective workload of team members

	Market Search	Mechanical Design	Raspberry Pi Coding	Microcontroller Coding	Analog Design	Handshake Protocols	Image Char. Decision	Image Binary Conversion	Power Analysis
Y. Emre İKİZ	✓			✓	✓	✓	✓		
Ö. Can KARAMAN	✓				✓				✓
Rafet KAVAK	✓		✓		✓			✓	
Ersin KESKİN	✓	✓		✓	✓		✓		✓
Ayşegül KILIÇ	✓		✓		✓	✓		✓	

From now on,

- Y. Emre İKİZ will focus on handshake methods, non-volatile data storage.
- Ö. Can KARAMAN will focus on more precise electronic circuits.
- Rafet KAVAK will focus on various image decomposition algorithms.
- Ersin KESKİN will focus on error correction algorithms.
- Ayşegül KILIÇ will focus on increasing the rate of byte transmission.

Table 5: New Respective workload of team members

	Market Search	Mechanical Design	Raspberry Pi Coding	Microcontroller Coding	Analog Design	Handshake Protocols	Image Binary Conversion	Power Analysis
Y. Emre İKİZ				✓		✓	✓	
Ö. Can KARAMAN	✓				✓			✓
Rafet KAVAK			✓			✓	✓	
Ersin KESKİN		✓		✓	✓			✓
Ayşegül KILIÇ			✓			✓	✓	

4.2. Gantt Chart

In Appendix A, one can see that our company's time table is not serial, it is actually parallel. By making our schedule as parallel as possible we guarantee the fastest approach. We do not need to wait for the former process to be completed to start and make progress on the project's next step.

4.3. Foreseeable Difficulties and Their Countermeasures

The main difficulties of this project arise from the fact that visible light communication (VLC) is not a fully stable data transfer system by itself since its success depends on the external conditions of the environment. This variable success of the VLC channel obligates us to make provision for possible failures of the project.

The variable success of VLC channels actually affects the whole project like a domino. Possible failure of the VLC channel accumulates the error throughout the whole process eventually project fails.

These foreseeable difficulties can be listed as:

1. Eliminating the external light source's effect on the analog electronics
2. Reaching to a data transfer rate greater than 10KB/sec
3. Operating analog electronics for long durations.
4. Operating shuttle for long periods
5. Recovering from an error reading during data transfer process
6. Synchronizing multiple subsystems.

To overcome these difficulties, a test of test and integration plans have been made such that each of the expected outcomes were observed before making any significant progress in the project. The test plans corresponding to the foreseeable difficulties aforementioned are:

1. Perform test procedure 3.3.1 until the system rejects external light conditions equally.
2. Perform test procedure 3.3.1 while measuring the transfer time within the software. Perform improvements using analog device theories until desired data transfer rate is realized without losing the results obtained in error rejection. If not possible, decrease the target transfer ratio until both conditions are satisfied.
3. Perform a hardware test on the analog electronics such that the system continuously transfers data and the transfer operation is logged over a long period, i.e. 12 hours. Confirm that the system is reliable and does not show different behaviour over long periods of loading.
4. Perform a hardware test on the shuttle, such that the device can commute between terminals over a long period without showing cosmetical damage on the device or the guiding bar. This ensures longer lifetime for battery and hardware.
5. After testing and integrating parts 1-4, integrate terminal and shuttle modules and perform a real loop closure test, where all 4 subsystems are working together. If successful, perform data transfer tests. Furthermore, introduce external errors to the system and see if the control algorithm is able to recover from external errors with minimum lost time in the operation.
6. Perform data transfer tests and externally disturb the system so that it loses synchronization, i.e. hold on to the Shuttle for a small duration that is larger than usual. Then observe that the system still performs tasks in a synchronized manner.

Upon completion of these tests, it can be concluded that the product is ready to be mass produced.

4.4. Cost Analysis

Although there are not many subsystems of the project when we look from the top-level, in order to achieve various ideas from communication theory we need reasonably fast and powerful processors.

By taking every different solution for each system and subsystem into consideration *Table 6* represents the overall cost analysis.

***Table 6**: Cost Analysis*

	Processor	Power Unit	Camera	Analog Circuitry	Motor	Motor Driver	Distance Sensor	Mechanic Tools
Terminal A	$30 - $40	$5 - $10	$8 - $10	$7	-	-	-	-
Shuttle	$20 - $30	$5 - $10	-	$2*7	$25-$40	$2 - $8	$3 -$5	$8 -$10
Terminal B	$30 - $40	$5 - $10	-	$7	-	-	-	-
Total	≅ $180							

Overall cost analysis in Table 6 shows us that the project cost will be in the range of $145-$190 which is strictly below the cost constraint of $200 for all possible solution approaches. Our company policy guarantees affordable prices.

4.5. Deliverables

The users are going to get the following items from the final product’s box:

- **Transmitter and Receiver Terminals:** Transmitter and Receiver Terminals are the parts that make up the non-moving parts of the system.
- **Shuttle:** Shuttle is the moving part of the project
- **Physically guided track:** The physically guided track indicates the system required for the vehicle to move.
- **Batteries:** The user will get three batteries to run the robot.
- **User Manual:** The user will get a user manual that contains information about the system, its components, and software.
- **Warranty:** Warranty is an official document showing that the system is guaranteed against errors that occur beyond the control of the user.

5. Conclusion

OWC is a trending technology as it uses the most basic media for data transfer, air. Today's unconventional methods of communication are becoming more and more insufficient as the world population and demand for data increases. For this purpose engineers constantly look for new ways to solve common problems. In this report NESET lays the conceptual groundwork for developing such an OWC system.

Firstly, the problem definition and system requirements are discussed to understand what is needed to be accomplished. Main goal of the project is to obtain a multi-terminal system with stationary and commuting parts that can communicate only via visible light and they are tasked to transfer an image data over a period of 2 minutes within a minimum of 5 cycles. Secondly, the solution approach to how to achieve the overall system control and solutions to subsystems to satisfy overall system requirements are discussed. The proposed solutions are supported with tests. Alternatives to present solutions are also provided to give a contrast between different approaches. Finally, future plans and expected difficulties of the system are discussed. Looking into past tests provide information for current success level of the project while investigating future test methods encourages putting more thought into engineering designs made. Both are very important to fully cover system requirements and prevent unexpected behaviours in the long term. A projected cost analysis is included to ensure project feasibility under proposed solutions. A list of deliverables is also available to recap the expected outcomes of the project. As a result, it can be deducted that the project development is on track and performed tests are promising. Future plans ensure the system integration is going to be performed flawlessly.

NESET looks into every possible source of error and inspiration of invention to deliver the cutting edge solution for its customers. As a young company, NESET is dedicated to becoming a leader in its sector and inspires other young engineers.

6. References

[1] "Finite-State Machine." Wikipedia. Wikimedia Foundation, November 25, 2019. https://en.wikipedia.org/wiki/Finite-state_machine.

[2] Zehendner, M., & Ulmann, M. (2017). Power Topologies Handbook. *TEXAS INSTRUMENT*, *1*, 48–58.

[3] http://www.everlight.com/file/ProductFile/PT204-6B.pdf

[4] https://cdn-shop.adafruit.com/datasheets/FLR-100A03-SR7.pdf

7. Appendices

Appendix A: Gantt Chart