Depth Perception Haptic System

Group 40

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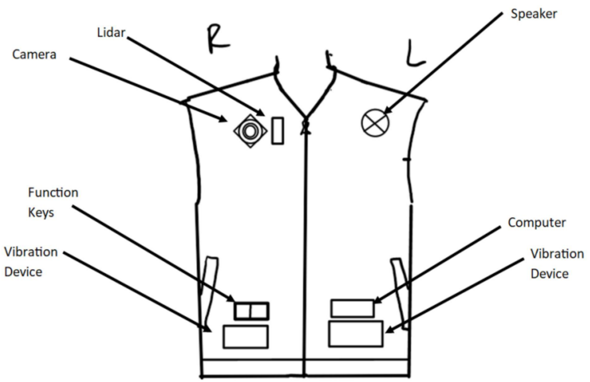
Outline

- Project Objective
- Requirements
- Software Discussion
- Hardware Discussion
- Administrative Details
- Testing
- Demonstration

Project Objective

The Depth Perception Haptic System is a wearable device that allows for hands-free navigation of indoor and outdoor spaces



Goals

Category	Goals
Physical Attributes	Lightweight, compact, durable
Usage & Maintenance	Responsive, rechargeable, long battery life, full range of motion (ROM)
User Interface	Simple, accessible, quick to learn
General Navigation	Encode distance and location of obstacles, alert to emergencies
Outdoor Navigation	Detect and describe curb presence, orientation, and magnitude

Requirement Specifications

Statement	Description	Value	Unit
Lightweight	Total weight of electronics, housings, and cloth.	< 10	lb
Compact	Thickness along all axes normal to the body.	< 2	in
Full Range of Motion (ROM)	ROM of shoulder joints before and after putting on device.	< 10	% diff
Large Buttons	Surface area large enough to contain braille.	> 0.25	in^2
Long Lasting, Rechargeable Battery	Time from full charge to depletion at 80% feedback level and all sensors active.	> 6	hrs
Haptic feedback that encodes distance	Provides a relative indication of distance (via feedback intensity) of arbitrarily shaped objects visible to the camera over a discrete range of intensities (including zero).	≥ 3	ct
Alert to proximal objects	Objects near the device trigger an unambiguous alert.	< 3	ft
Quick Response Time	Time it takes for the device to send a haptic response from a spontaneously appearing obstacle.	< 900	ms

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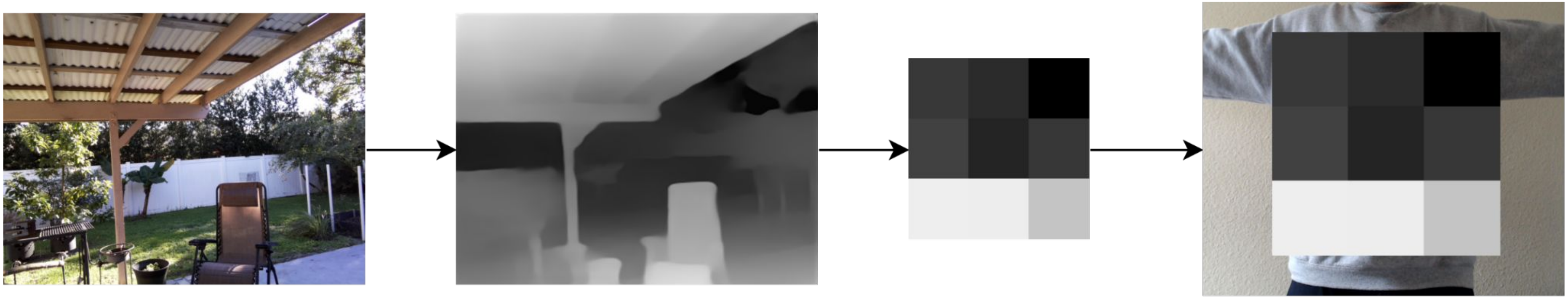
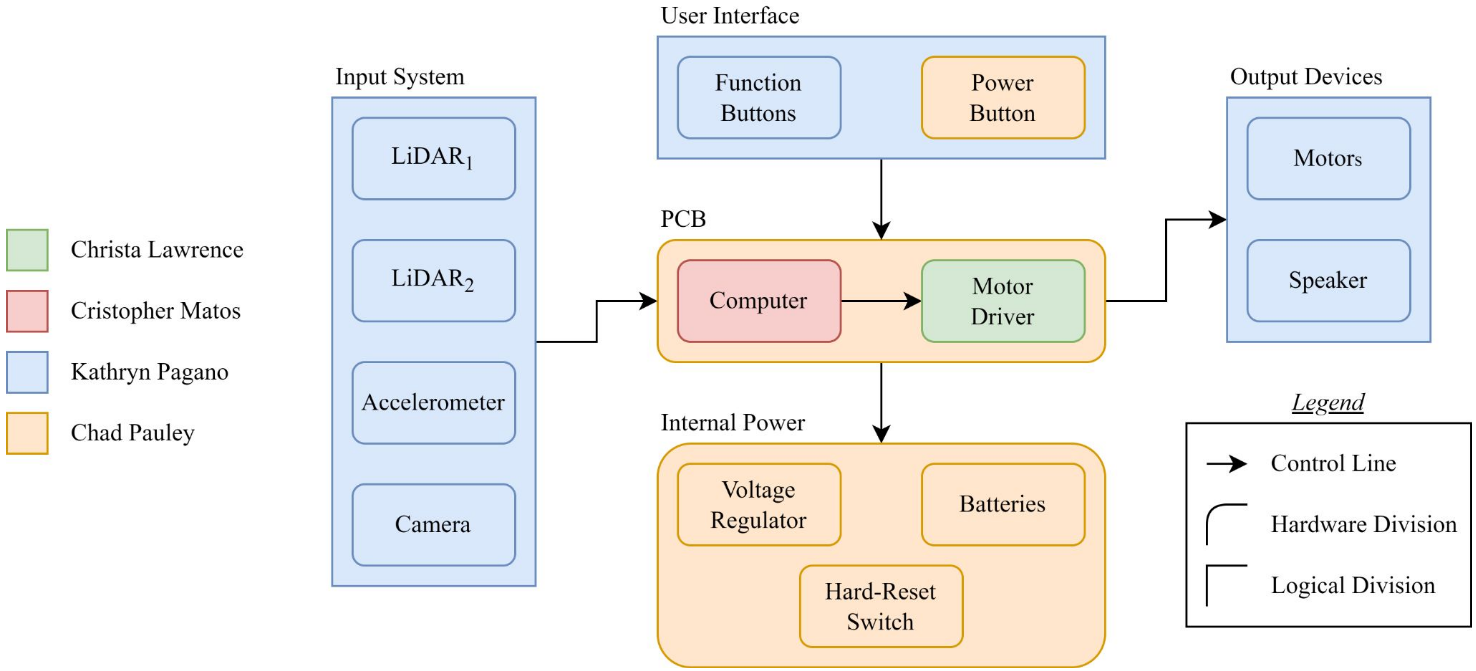
Solution Approach - Obstacle Avoidance

- Combine computer vision with LiDAR to map objects in the environment to the user's body via haptic (vibration) feedback
    - Minimizes # of sensors, maximizes input data

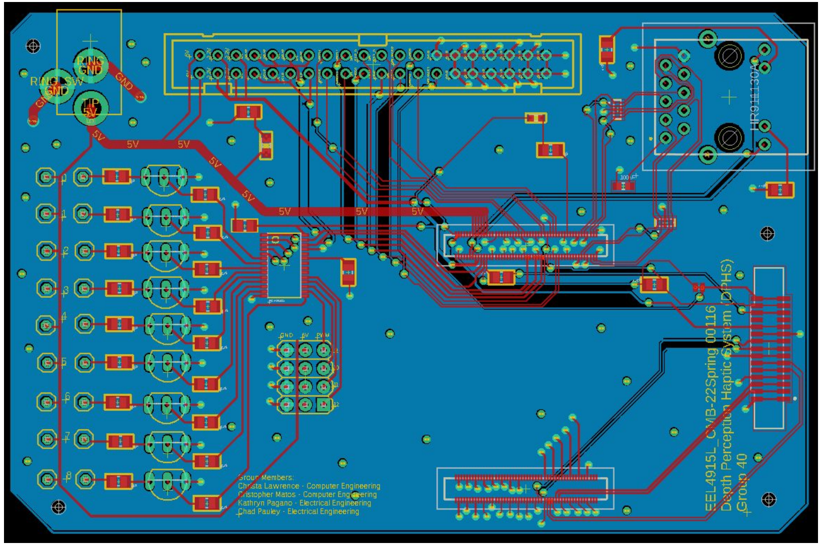


Overall Block Diagram



Hardware Design Approach

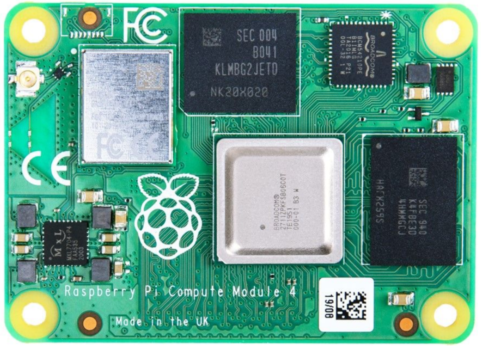
Always plan to make a prototype, because you'll end up building one anyway



Design Considerations

- Minimize power consumption
- Low resolution output
- Minimize number of sensor units while maximizing input data (CV + LiDAR),
- Ensuring all clock and input data is coherent
- Enough outputs to ensure future development and testing potential

Major Component Considerations



- Raspberry Pi Compute Module 4 (CM4)
  - Price
  - Hardware independence
    - Entire project run on ARM CPU (and integrated GPU)
  - Required RAM and embedded memory
  - Availability of schematics
  - Ability to modify carryout board
  - GPIO availability (up to 5x UART, 5x I2C, 1x SDIO, 1 PCM, 2x PWM, 3x GPCLK, two MIPI CSI channels and multiple voltage output lanes including 3.3V and 1.8V)

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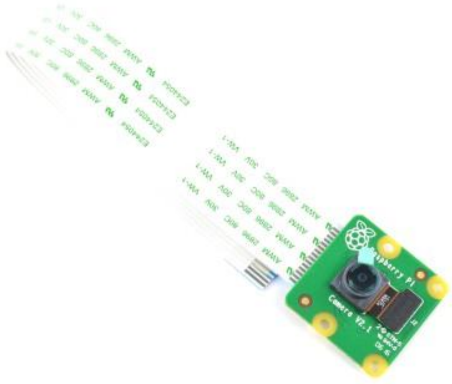
Raspberry Pi Camera



Model:Raspberry Pi Camera Module 2
Resolution
- 8-megapixel
- 3280 x 2464 still frame

Video mode
- 1080p30, 720p60, 480p90

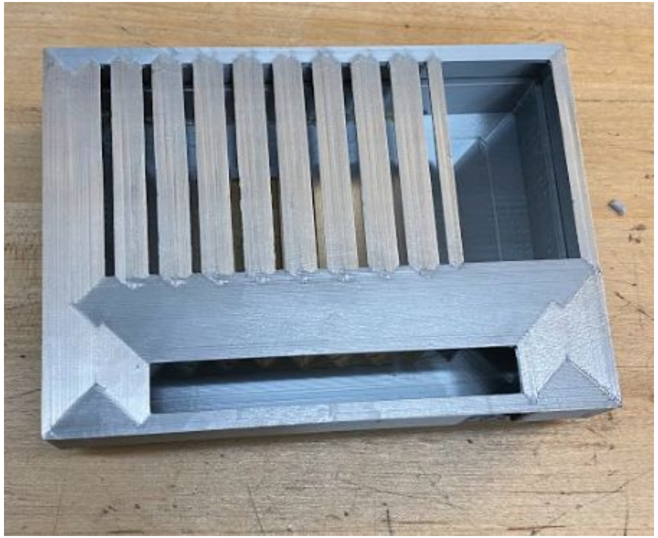
Price
- $25.00

Board size
- 23.86 x 25 x 9mm

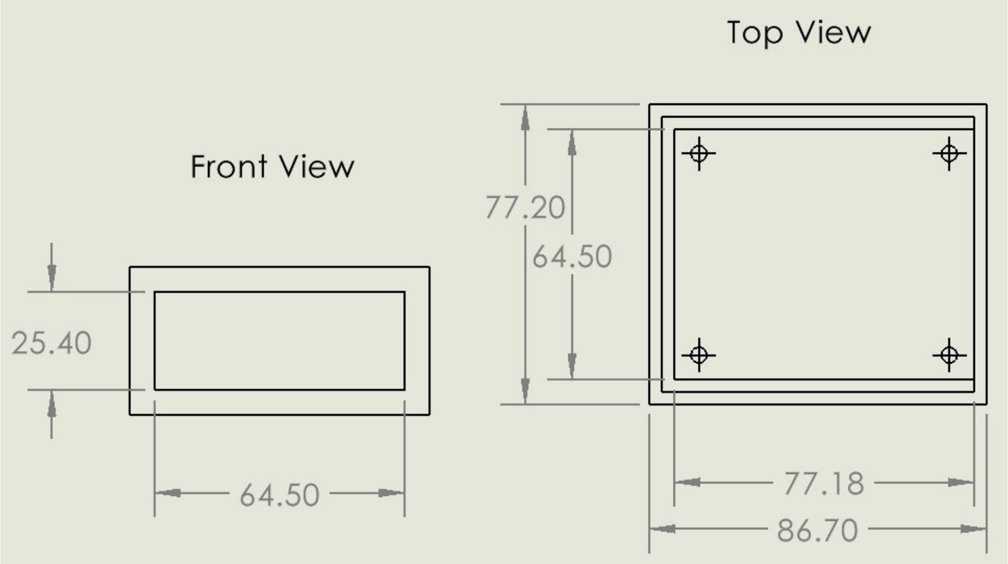
Onboard processor
- No

The camera module is incredibly small and can easily be concealed.
This camera is compatible with the Raspberry Pi board and can be connected using either a 15 pin connector or 22 pin adapter ribbon to work with the board.
It uses the Camera Serial Interface Type 2 (CSI-2).
Software Controlled directly by board, no special drivers needed.

PCB Housing



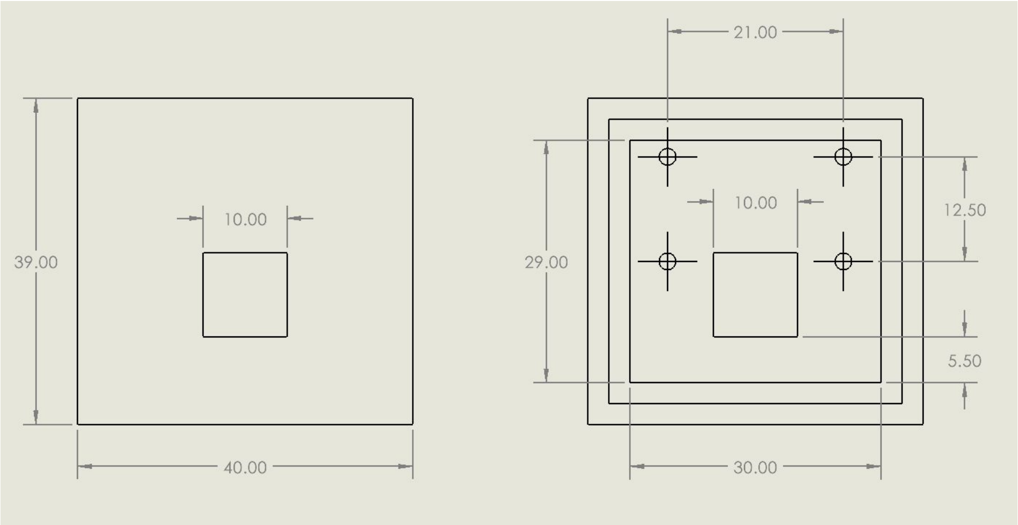
Raspberry Pi Case Angled View



Raspberry Pi Case Approx. Measurements

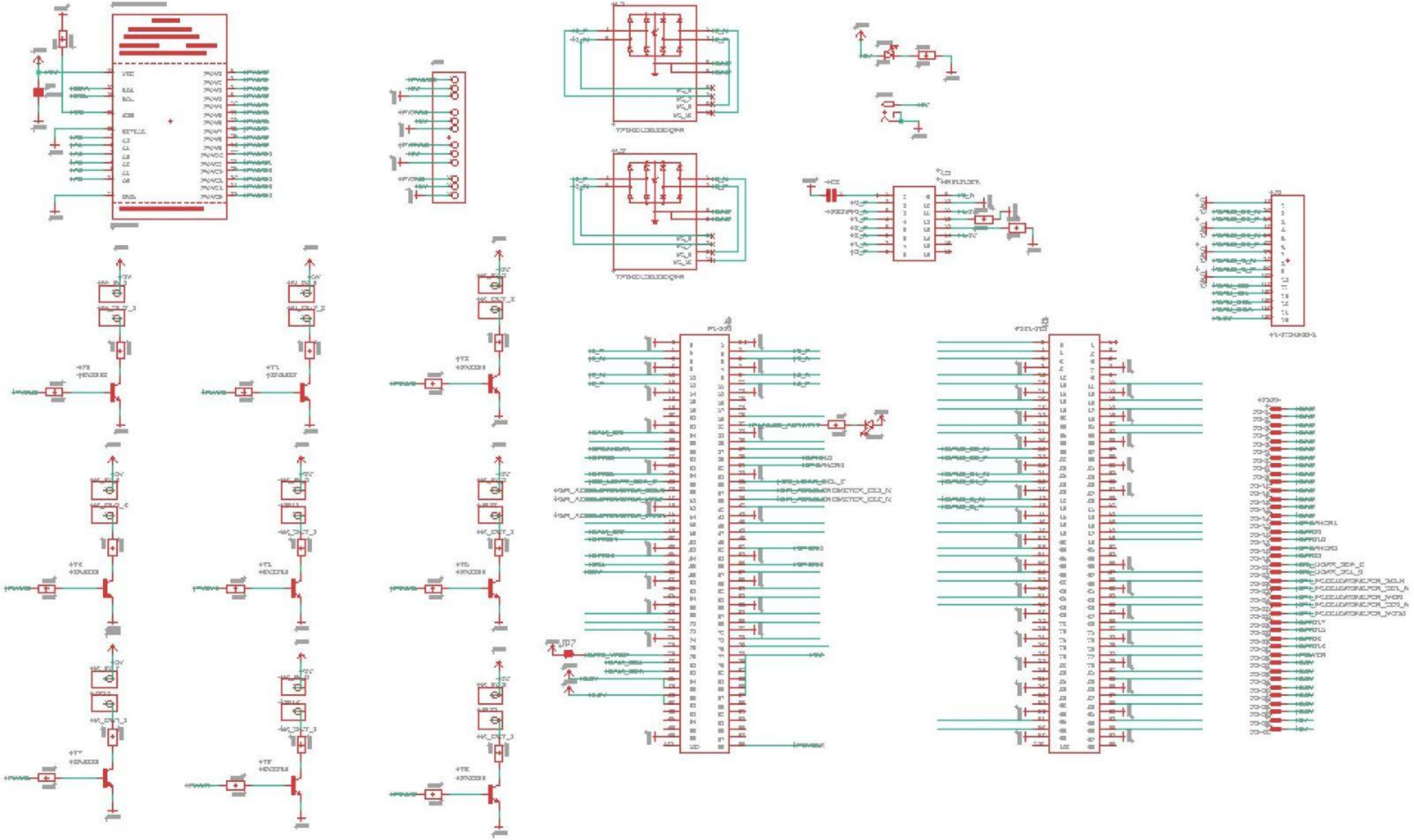
Raspberry Pi Camera Case

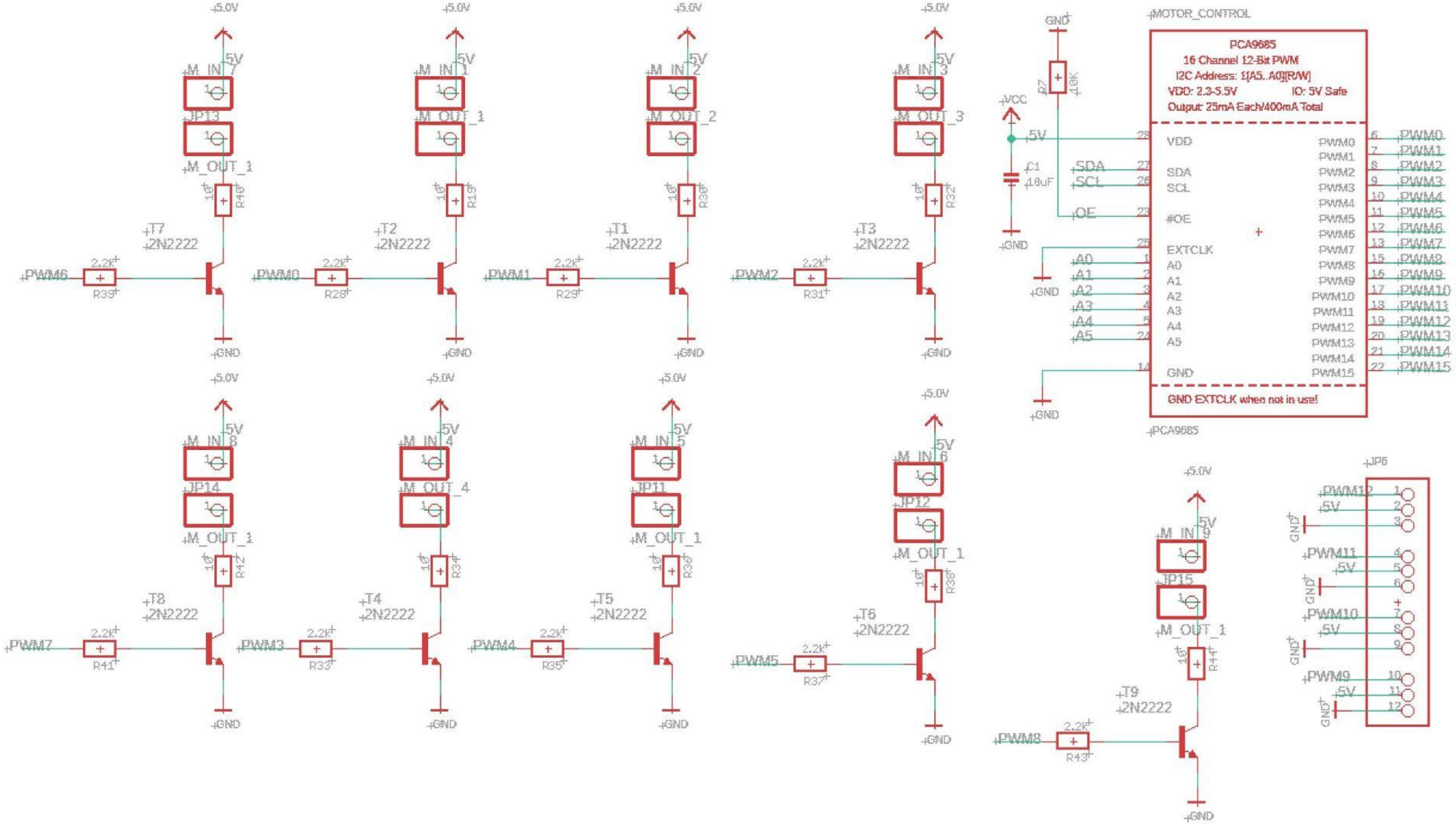
Raspberry Pi Camera Case



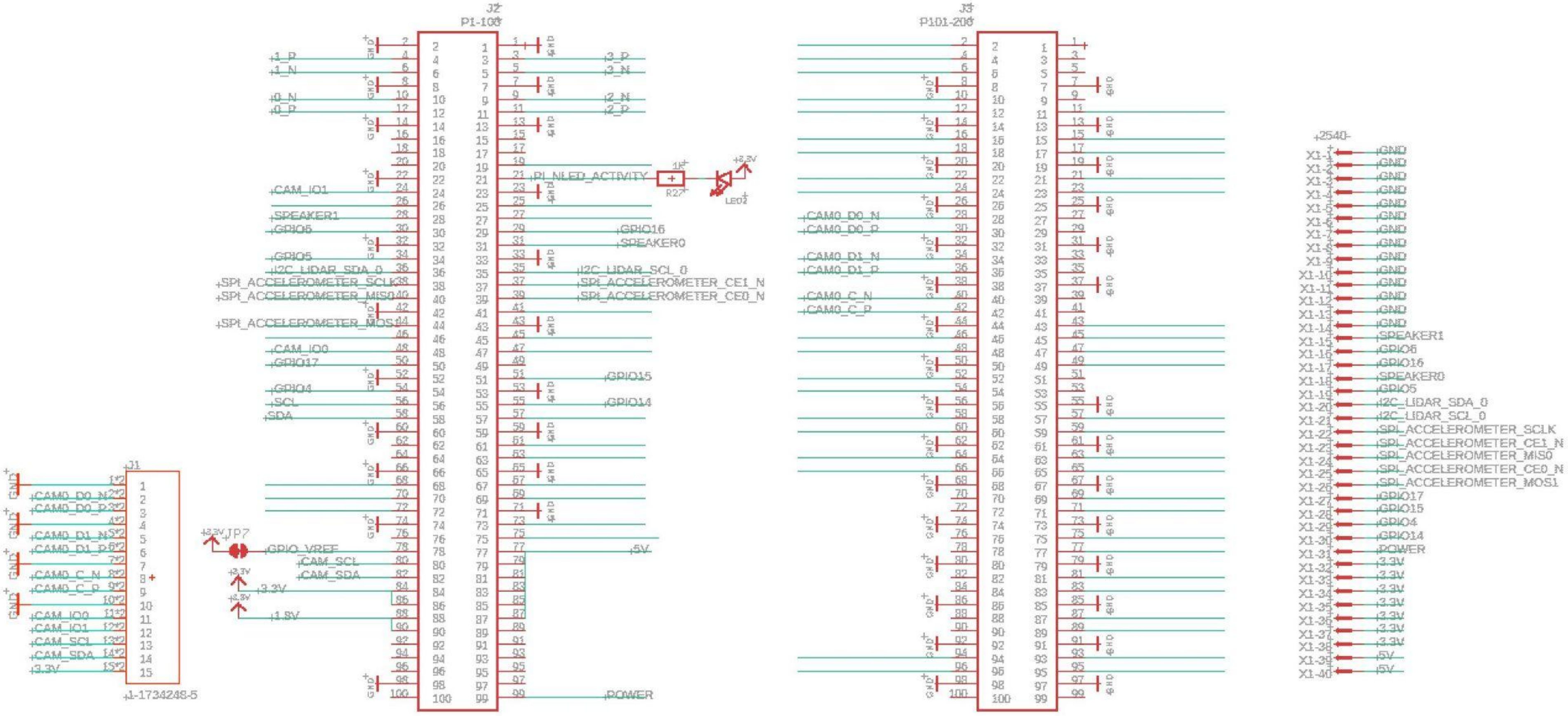
Raspberry Pi Camera Case Approx. Measurements

Keeps moisture and dirt out of the camera's sensitive components and ensures durability.

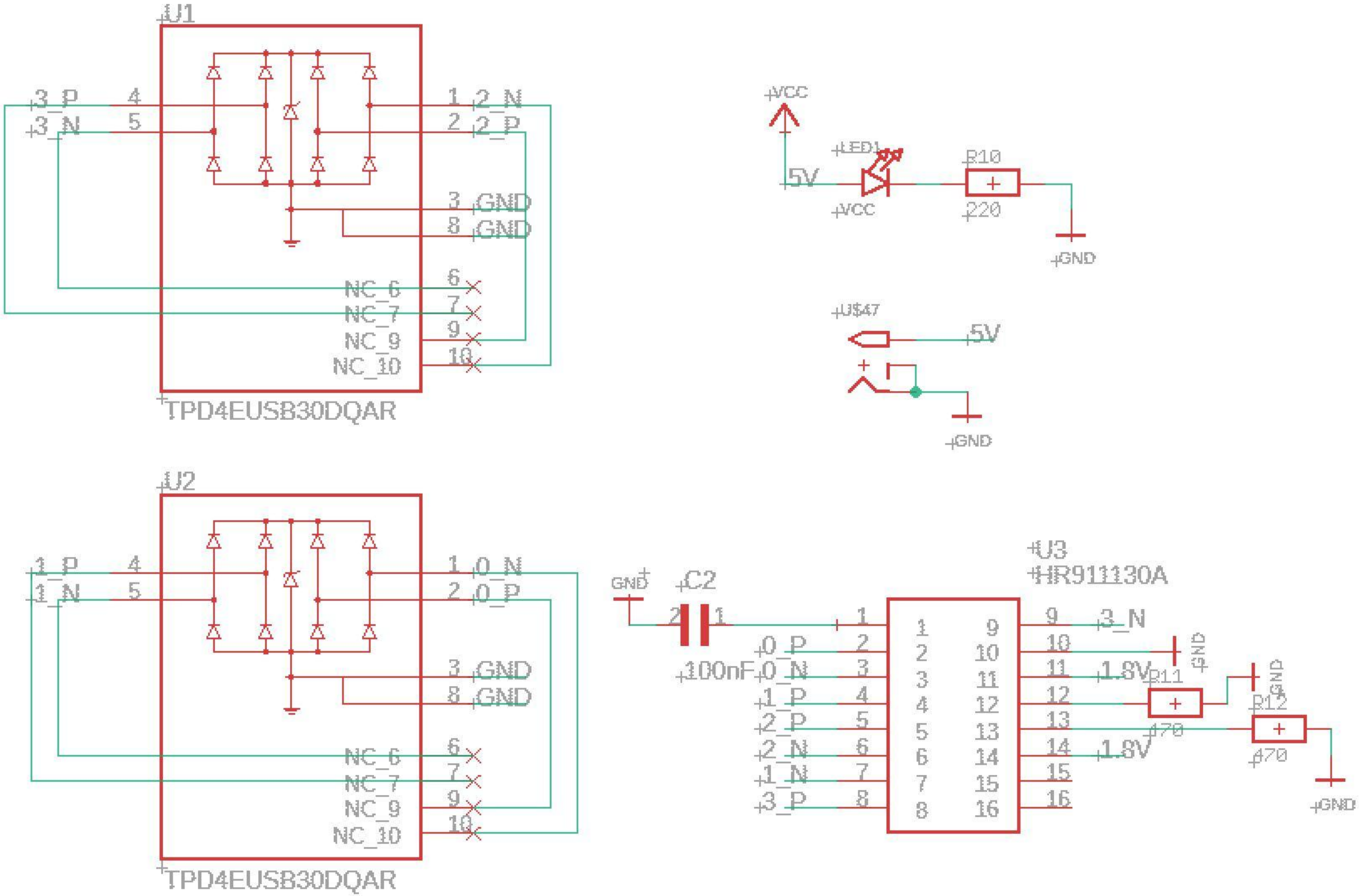




PCA9685
16 Channel 12-Bit PWM
I2C Address: 1[A5..A0][R/W]
VDD: 2.3-5.5V
IO: 5V Safe
Output: 25mA Each/400mA Total
GND EXTCLK when not in use!
MOTOR_CONTROL
VDD
SDA
SCL
#OE
EXTCLK
A0
A1
A2
A3
A4
A5
GND
PWM0
PWM1
PWM2
PWM3
PWM4
PWM5
PWM6
PWM7
PWM8
PWM9
PWM10
PWM11
PWM12
PWM13
PWM14
PWM15
VCC
C1
10uF
R7
10K
5.0V
5V
GND
2N2222
T1
T2
T3
T4
T5
T6
T7
T8
T9
2.2K
M_IN_1
M_IN_2
M_IN_3
M_IN_4
M_IN_5
M_IN_6
M_IN_7
M_IN_8
M_IN_9
M_OUT_1
M_OUT_2
M_OUT_3
M_OUT_4
JP5
JP11
JP12
JP13
JP14
JP15

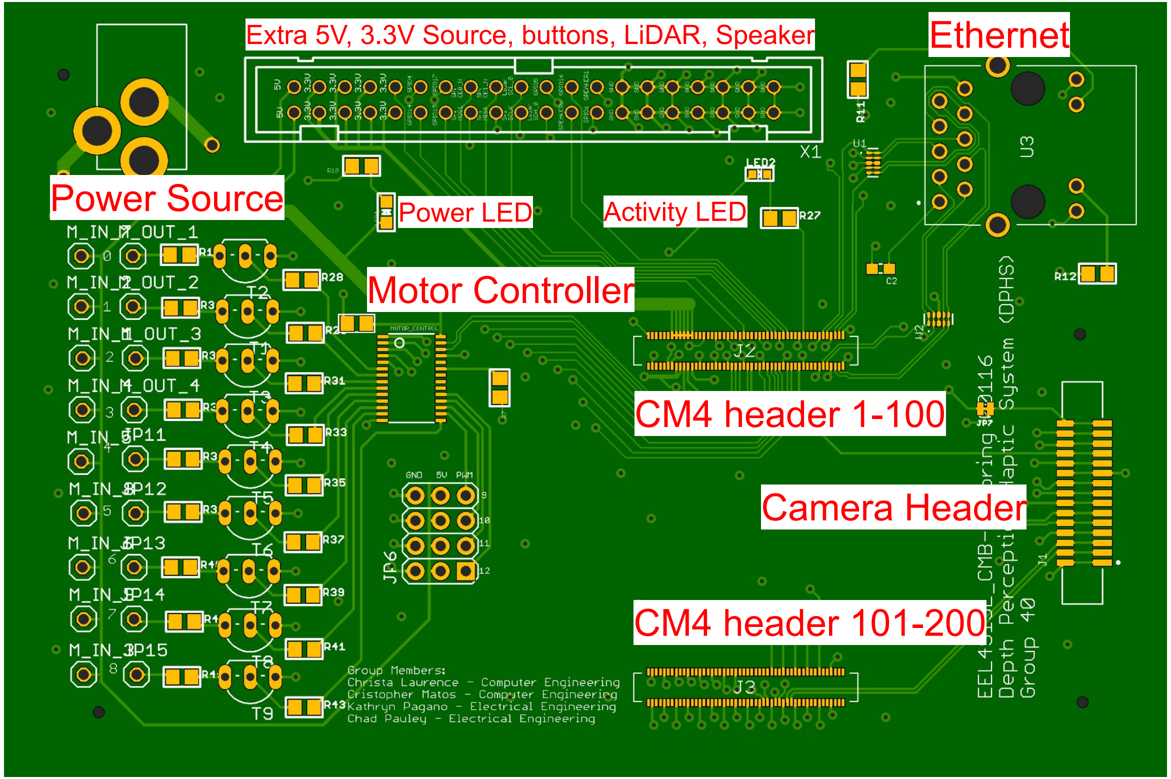


- 2 LiDARs (I2C)
- Speaker (PWM)
- Soft power off (button tied to GND)
- Raspberry Pi Camera (15-pinout)
- 5 programmable GPIO pins for buttons
- Motor Controller Chip (I2C -> PWM)



U1
3_P
3_N
4
5
1
2
2_N
2_P
3
8
GND
GND
NC_6
NC_7
NC_9
NC_10
6
7
9
10
TPD4EUSB30DQAR
VCC
LED1
5V
VCC
R10
220
GND
U$47
5V
GND
U2
1_P
1_N
1_0_N
2_0_P
TPD4EUSB30DQAR
U3
HR911130A
GND
C2
100nF
0_P
0_N
1_P
2_P
2_N
1_N
3_P
3_N
1.8V
R11
470
R12
470
1.8V
GND

Board layout



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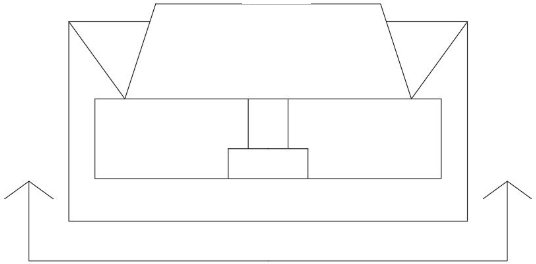
4 Programmable Buttons

1) Outdoor Moode
2) Spare
3) Low Power Mode
4) General Mode



Section "A -- A"

Button Cross-section

On/ Off Switch	1 Outdoor Moder	2 Spare	3 Low Power Mode	4 General Mode

Button Layout

Two Levels of Power Control

- Button Power Off (Software Controlled)
  - Button connected to GPIO GLOBAL_EN set driven low sets device to minimum power usage (around 15μA).
- Switch Power Off (Hardware Controlled)
  - Physical switch between the batteries and voltage regulator to allow the batteries and device to maintain longevity as well as function as hard reset for any potential errors.

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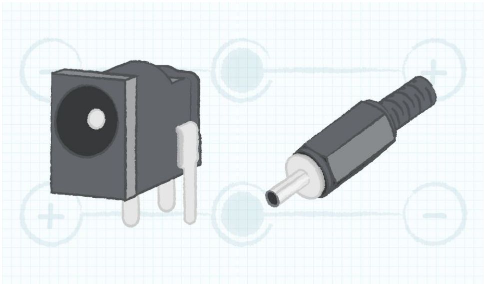
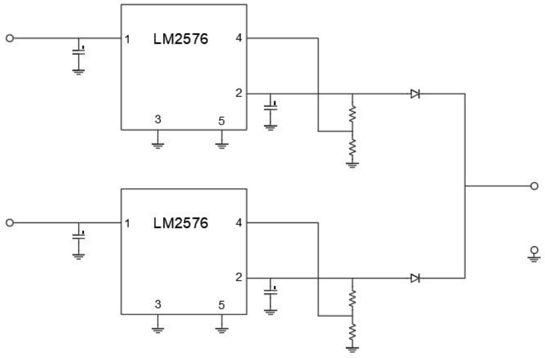
Voltage Regulator

Mounted separately to batteries to have 5V source instead of 12V+

A TAMAYA plug is used to charge the device (as shown below)

Barrel Jack connects to the board





Power Considerations

- Battery must be able to supply 3A with a voltage source between 5V and 30V.
- Due to design constraints in creating a power bus; the power for the CM4 and PWM motor control are differentiated as a primary 5V pin and VCC pin respectively on the board to evenly split current and effectively half the needed width for the bus channels on the PCB.

Electronic Code of Federal Regulations

- The device must be less than or equal to the maximum unit of energy consumption (UEC) for the appropriate product class and battery rating

Product Class	**Product Class Description**	**Rated Battery Energy (Ebatt)**	**Special characteristics or battery voltage**	**Maximum UEC (kWh/yr)**
1	Low-Energy	≤ 5 Wh	Inductive Connection	3.04
2	Low-Energy, Low-Voltage	<100 Wh	<4V	$.1440*E_{bat}+2.95$
3	Low-Energy, Medium-Voltage		4-10 V	For E_{batt} <10 Wh, 1.42 kWh/y $E_{batt} \geq 10$ Wh, $0.0255 * E_{batt} + 1.16$
4	Low-Energy, High-Voltage		>10V	$0.11 * E_{batt} + 3.18$

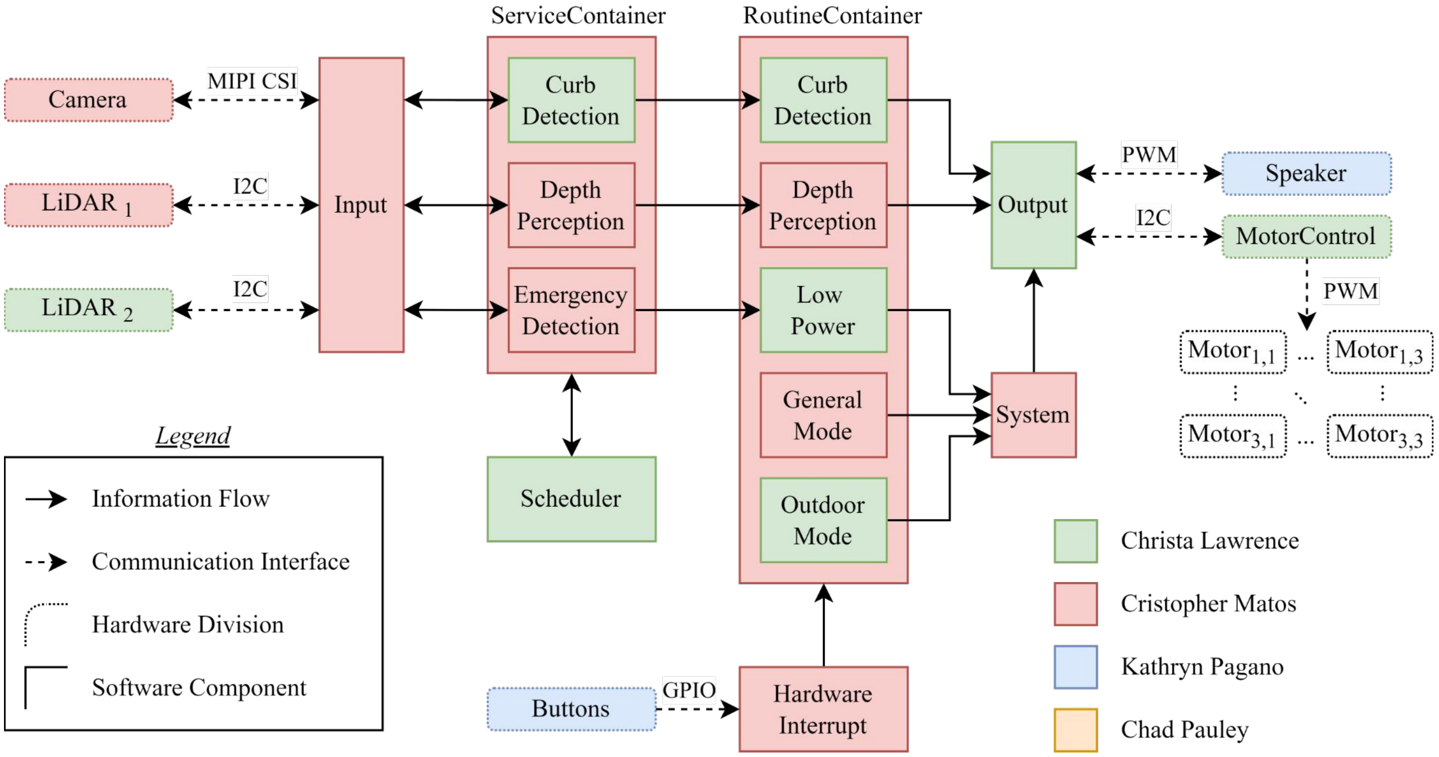
Power Considerations

Part	Idle	Full Use
Camera	200mA	200-250mA
2x lidar (Garmin LIDAR-Lite v4)	2mA	85mA
Accelerometer (ADXL345)	.1uA	40uA
CM4	The lowest shutdown power consumption mode is with the GLOBAL_EN driven low, typically is 15uA. With GLOBAL_EN high but software shutdown the typical consumption is 8mA. Idle power consumption is typically 400mA	Operating power consumption is typically around 1.4A again this greatly depends on the Operating System and the Tasks, goes up to 3A.
Motor Controller (PCA9685)	25mA	25mA
Speaker	0	1.7mA
Individual Motor	0	9-25 mA depending on intensity

Hardware Design Changes Made Over Time

- Removal of HDMI interface as later noted as unnecessary and to reduce size of PCB
- Removal of SD memory storage due to the need for more GPIO pins
- Removal of voltage regulator chip on primary PCB board due to concern of electric shock
- Change from using PWM with MOSFET connection which would control voltage of haptic motors with duty cycle to a direct connection with a simple diode and capacitor controlled by the programmable values set by analog
- Addition of ethernet connector to PCB for troubleshooting

Software Overview



Depth Perception Approach

- Problem: Need distances of objects located in front of the user
  - Existing products use:
    - Multiple distance sensors placed along body
    - One distance sensor, actively manipulated by user
  - Conflicts with our goals:
    - Few sensors (For full ROM and comfort)
    - Hands-free operation
- Solution: Combine computer vision (CV) with LiDAR to estimate depth

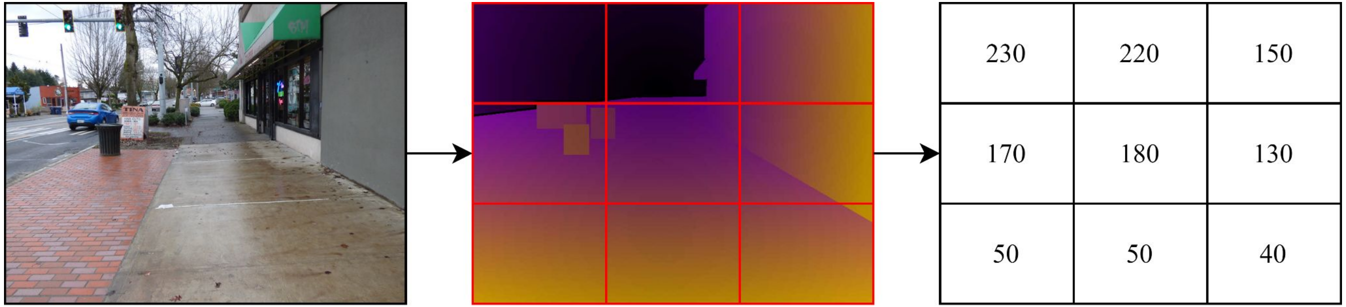
Approach Motivation

- Explosion of research and development in monocular depth estimation for mobile devices (Ignatov et al., 2021)
  - Some models (including MIT Licensed) already exist online
- Prospect of combining depth inferencing with LiDAR

Inference using Intel's Midas/v2_1_small on TensorFlow Lite

Depth Sensing Procedure

1. Use MiDaS to create a depth map of the space in front of the user
2. Divide map into regions
3. Find one representative value per region
4. Set motor intensity based on value



Raw Image — Image after Depth Inference — Reduced Resolution Depth Map

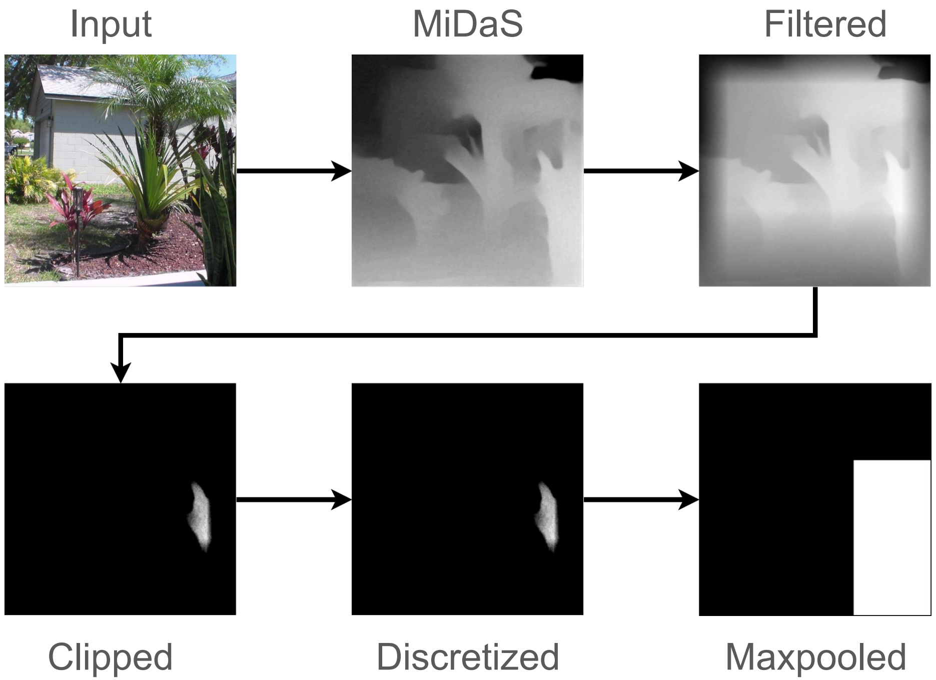
Raw Image sourced from (SDOT, 2015)

Representative Value and Motor Response

1. Subtract box filter
2. Clip
3. Discretize to N levels
4. Maxpool
5. Compare with previous

Motor intensity varies linearly with estimated depth

More complex response patterns likely require a greater time to learn



Latency Reduction and Accuracy Penalty

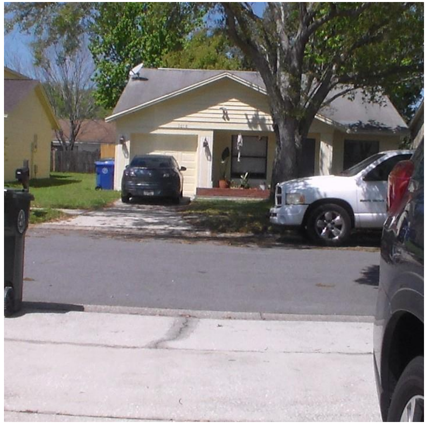
- Alibaba MNN Framework with UINT8 quantized weights of MiDaS v2.1 Small
  - Maximum inference time: 302 ms, 3.3 FPS
  - 3.1x speedup from FP32 model on Tensorflow Lite

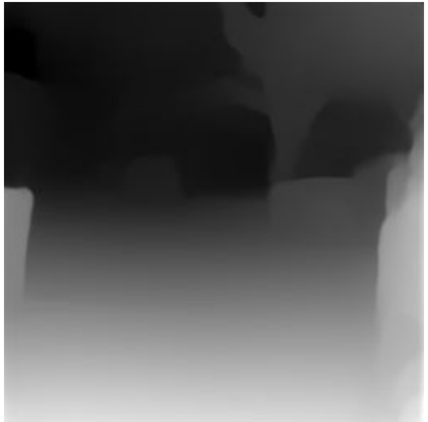
	TF Lite[1]	TF Lite w/ XNNPACK	MNN[2]
Floating Point Weights	T_1 = 1,906 T_2 = 1,213 T_4 = <u>948</u> T_8 = 1,619	1,170 655 511 1,136	744 445 398 578
Int Quantized Weights[3,4,5]	1,111 670 468 1,249	1,106 682 467 1,179	901 486 <u>302</u> 454

Maximum inference times (ms) for various thread counts T_i. All benchmarks set to 5 warm up runs, 50 runs, VideoCore temp below 70.0 ℃.
[1] Results from TF Lite linux arm benchmark tool
[2] Results from MNN model benchmark tool
[3] Weights quantized using RedWeb V1 dataset
[4] INT8 quantized weights for TF Lite from default optimization tool
[5] UINT8 quantized weights for MNN from the quantization tool. KL divergence for features, max absolute value for weights

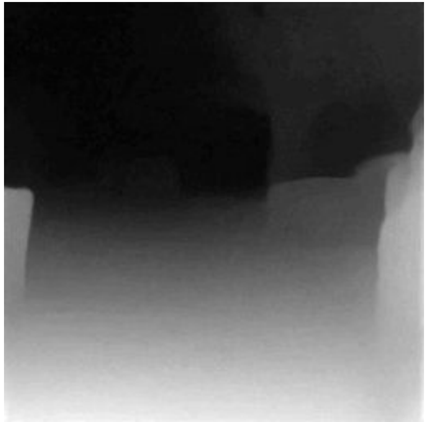
Latency Reduction and Accuracy Penalty

- Minor reduction in accuracy when using UINT8 weights versus FP32
  - Inference time greater priority than pixel-for-pixel accuracy
  - Essential features preserved





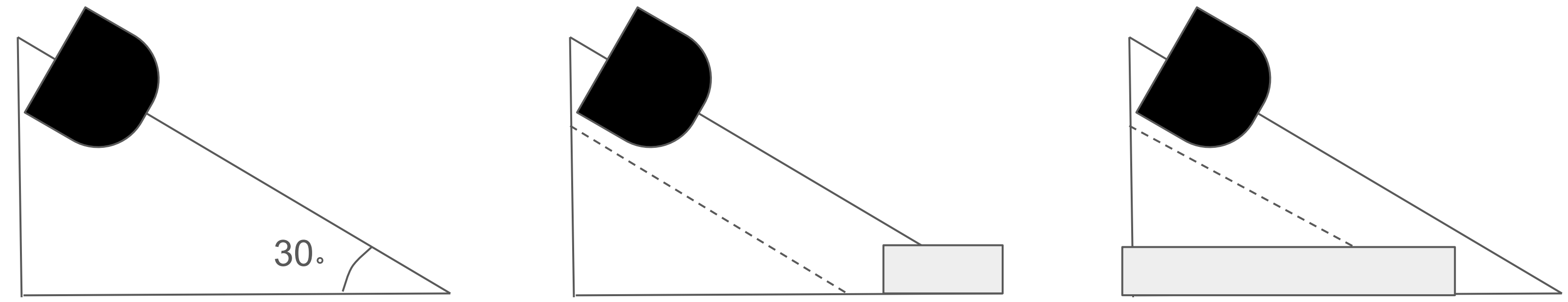
FP32



UINT8

Curb Detection

- LiDAR angled downward to poll for changes in floor height
- Maintains finite length queue which detects range changes over time
  - If the index of the maximum of the curb is before the index of the minimum, step down
  - Otherwise, step up



Emergency Detection

- Forward-facing LiDAR programmatically connected to motor device central to the chest
  - Linear haptic response to distance detected by device
- When the threshold distance (3 ft) is detected, the system will force all motors to vibrate until the obstacle is no longer present
  - All motors 100% haptic feedback intensity at 5 Hz and 50% duty cycle

Successes and Difficulties

Part Availability (CM4 and Voltage Regulator)

Shipping Dates

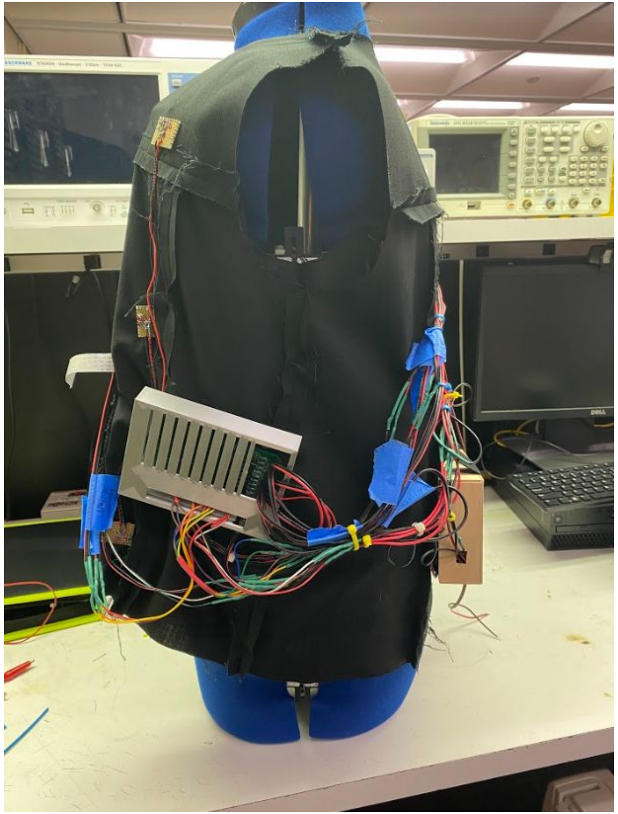
PCB arrangement on 2-layer design

CV Runtime Reduction

Budget

Item Type	Quantity	Actual Cost	Description
LiDAR	2	$60	Garmin LiDAR
Accelerometer	1	$19	ADXL345
Camera	1	$25	Raspberry Pi Camera
Speaker	1	$11	MakerHawk Speaker
Haptic feedback	Set acquirement (20)	$16	Tatoko flat coin motors
Compute Module	2	$215	Raspberry Pi Compute 4 Module 4GB (+Replacement)
Fabric	1	$25	
Battery	3	$15	12V, 4800mAh
Misc. Electronics & Materials		$100	
Shipping		$37.93	Shipping on parts
Current Total		=$576	

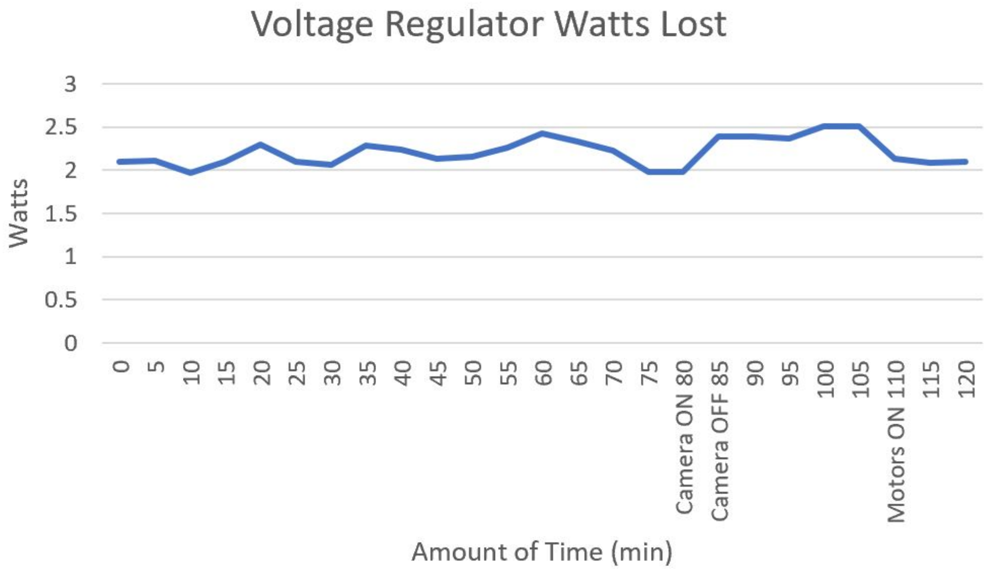
TESTING



Testing Considerations

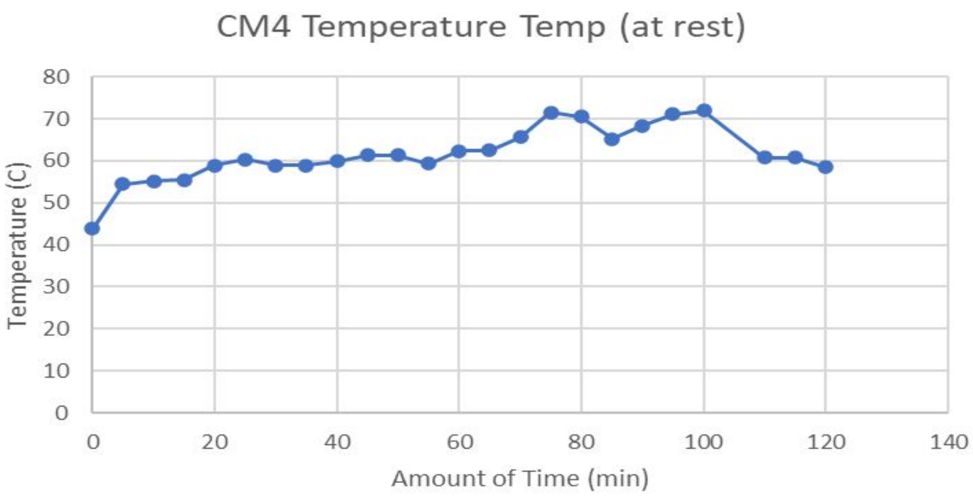
- Fabric can muffle sounds and haptic feedback: Can the user hear the audible alerts and feel the haptic vibrations?
- Can the user effectively avoid approaching obstacles?
- How long does the battery actually last?
- What is the voltage coming out of the regulator?
- Do the lidars provide distance based alerts?
- Do the buttons work?
- Do we have a successful Field test?

Hardware Testing



Voltage Regulator Waste	
Time (min)	Watts
0	2.09979
5	2.11275
10	1.97136
15	2.0922
20	2.2925
25	2.09304
30	2.06397
35	2.28975
40	2.24155
45	2.13092
50	2.15
55	2.25624
60	2.42736
65	2.33
70	2.23
75	1.97802
Camera ON	1.978
Camera OFF	2.38386
90	2.384
95	2.369
100	2.50295
105	2.5029
Motors ON 1	2.13486
115	2.08119
120	2.0941

Hardware Testing



CM4 Temperature	
Time (min)	Temp
0	43.8
5	54.5
10	55.1
15	55.5
20	58.9
25	60.3
30	58.9
35	58.9
40	59.9
45	61.3
50	61.3
55	59.4
60	62.3
65	62.5
70	65.7
75	71.5
80	70.5
85	65.2
90	68.4
95	71.1
100	72
110	60.8
115	60.8
120	58.4

COMPONENT & REQUIREMENT TESTING

FEEDBACK

TESTING OBSERVATIONS

FULL INTEGRATION FIELD TEST

Requirement Specifications

Statement	Description	Value	Actual	Y/N	Unit
Lightweight	Total weight.	< 10	4.0	Y	lb
Compact	Thickness along normal to the body.	< 2	1.8	Y	in
Full Range of Motion (ROM)	ROM of shoulder joints.	< 10	0	Y	% diff
Large Buttons	Surface area of buttons.	> 0.25	0.28	Y	in^2
Long Lasting	Time from full charge to depletion.	> 6	2.0	N	hrs
Haptic feedback that encodes distance	Detectable feedback levels.	≥ 3	8	Y	ct
Alert to proximal objects	Objects near the device alert.	< 3	1.5	Y	ft
Quick Response Time	Latency of computer vision.	< 900	302	Y	ms

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References

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Ranftl, Rene, et al. “Towards Robust Monocular Depth Estimation: Mixing Datasets for Zero-shot Cross-dataset Transfer.” IEEE Transactions on Pattern Analysis and Machine Intelligence, 2020, https://arxiv.org/abs/1907.01341.

SDOT Photos. “Columbia City Sidewalk Repair Project.” flickr, 16 Dec. 2015, https://www.flickr.com/photos/sdot_photos/23168490614. Image. Used in its resized form, and colored over with gradients to depict depth. Licensed under CC BY-NC 2.0.

Zhang, Ziyu, et al. “A Simple Baseline for Fast and Accurate Depth Estimation on Mobile Devices.” 2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), 2021, https://openaccess.thecvf.com/content/CVPR2021W/MAI/papers/Zhang_A_Simple_Baseline_for_Fast_and_Accurate_Depth_Estimation_on_CVPRW_2021_paper.pdf.

Questions?