

LASER TRACKING GIMBAL

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Abstract

This project uses a vision-guided two-axis gimbal to autonomously track a soccer ball for real-time on-device streaming and inference. A camera mounted on the gimbal will stream frames to the laptop, where an object detection model will identify the ball and estimate its position. The laptop will convert this information into movement commands, which are transmitted to a custom PCB via Ethernet (or CAN). The PCB acts as the main control unit to orchestrate the brushless motors and the closed feedback loop for moving the gimbal. The final product will have the gimbal successfully moving with the movement of the soccer ball, with a laser pointing at the ball at all times.

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1. Introduction

Modern day sports broadcasting typically relies on a camera man to track the ball movement throughout the game. This makes it difficult to sustain it for a long time in addition to capturing fast paced movements across milliseconds. Furthermore, this is especially difficult in settings where

lower-production is required with fewer staff possibly missing out on capturing crucial moments within a game. This project can help smaller teams with fewer staff produce more consistent footage. However, our project still requires human operators and is intended to work in tandem with human operators rather than eliminate oversight. Finally, the gimbal must have safety constraints of a physical emergency stop, and it should never be aimed at people.

1.1 Solution

Our solution is a vision-guided camera platform that autonomously keeps a soccer ball near the center of the camera frame. A USB camera mounted on the two-axis gimbal captures a live video stream. A laptop runs a real-time object-detection model to identify the soccer ball and calculate the difference between the ball's bounding-box center and the camera-frame center. This difference in space, along with knowing the offset between the laser and camera mounts, allows us to correct the laser to point toward the ball more accurately.

The laptop communicates movement commands to an STM32 microcontroller on a custom PCB. The microcontroller reads motor encoder feedback, drives the motors through the inverter stage, and returns telemetry to the laptop. The firmware will implement several states, such as a searching state, initialization, calibration, idle, tracking, and fault states. Camera calibration will calculate the frame center through the camera's intrinsic parameters.

1.2 Visual Aid



1.2.1 Physical Design

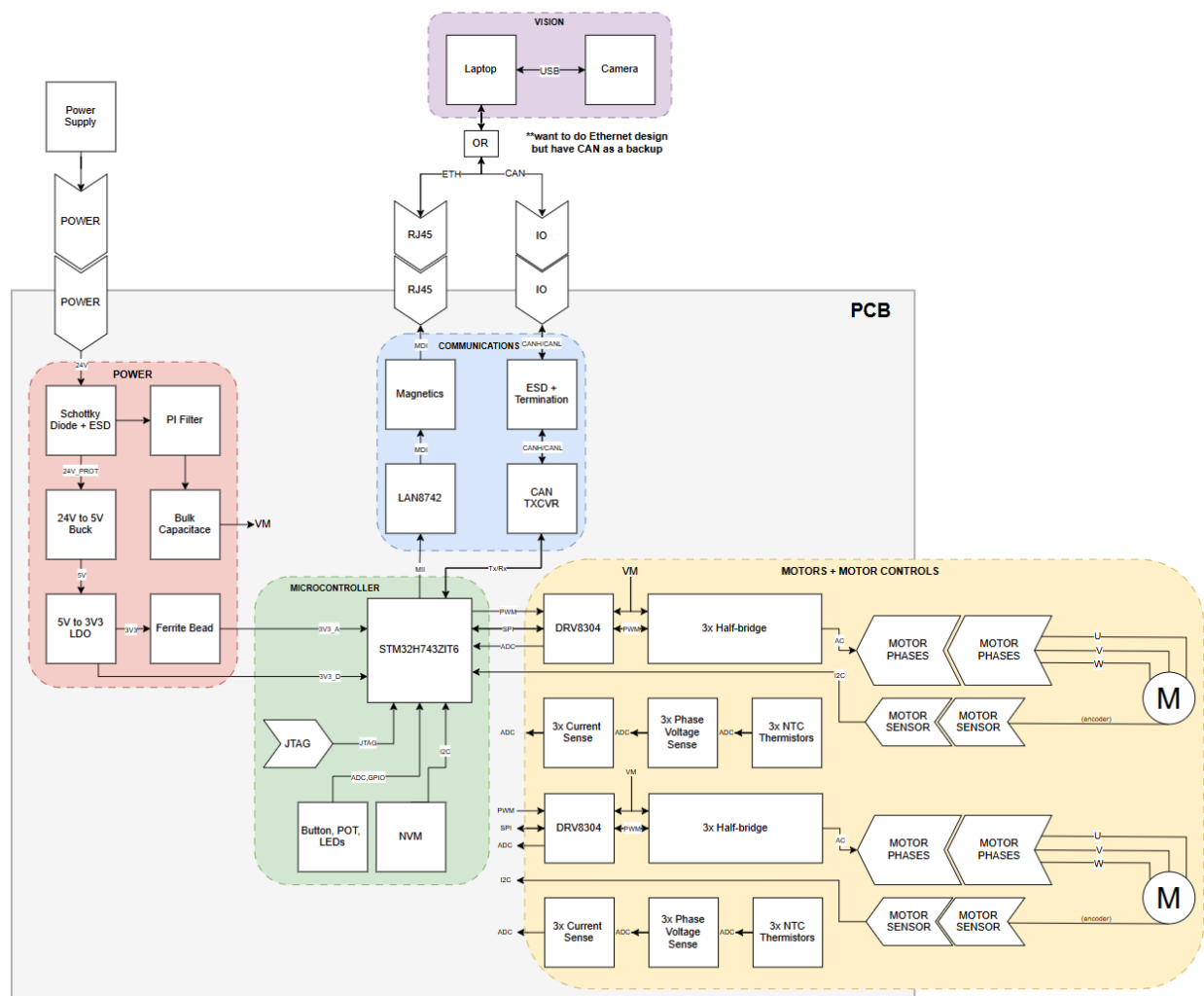
Overall size should be around 20cm x 20cm x 25cm, not including the tripod. The base will take around 15x15cm, with the PCB in a small enclosure around 10x10x4cm. The power, ethernet, and other connectors will be on the side. The pan motor will sit at the base and rotate the whole upper assembly left and right, while the tilt motor will be mounted on a bracket above the pan motor that tilts the camera up and down. The camera and laser will be mounted in the center on the same bracket.

1.3 High Level Requirements

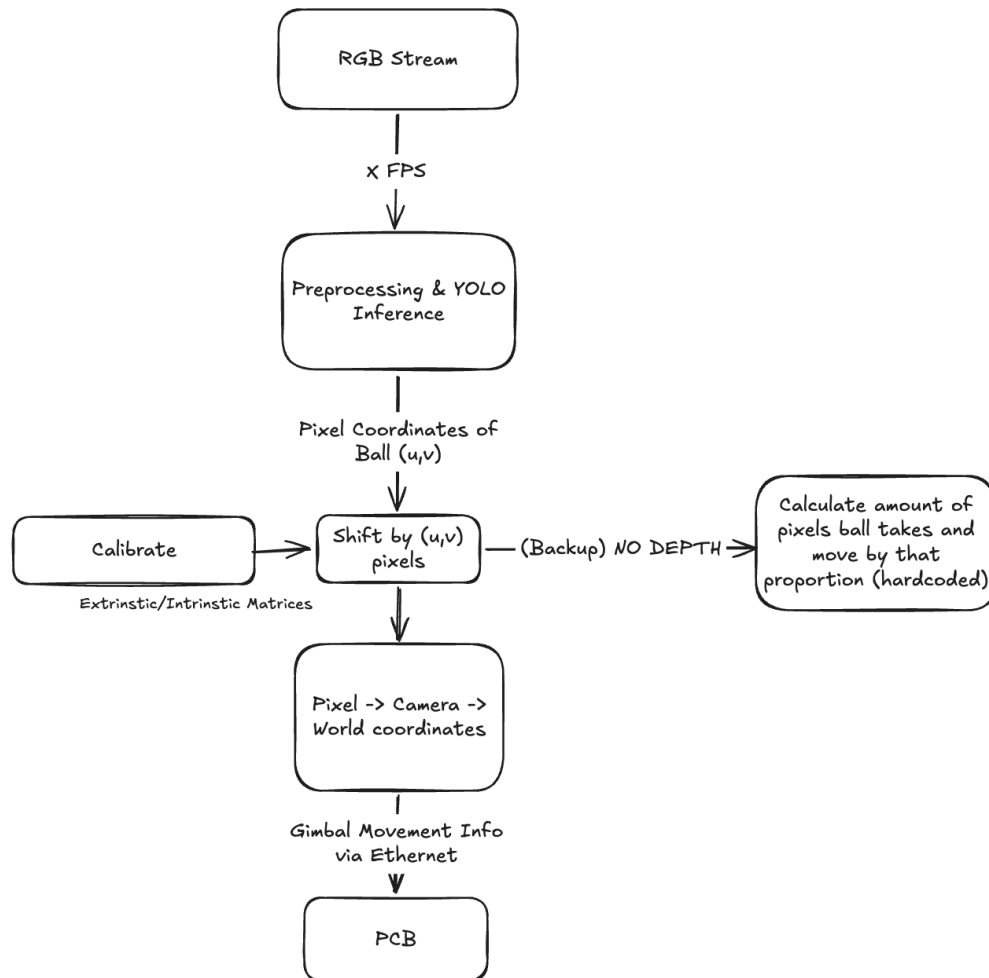
- While the soccer ball is moving, the system should keep the ball visibly within the center 80% of the screen's ROI (Region of Interest) for at least 30 seconds.
- The system should detect the soccer ball and update the gimbal's position at least 5 times per second (200ms).
- After the soccer ball initially re-enters the frame, the camera system should lock on and center the ball within the frame within 1 second.

2 Design

2.1 Hardware



2.1 Vision



2.2 Subsystem Overview

2.2.1 Power

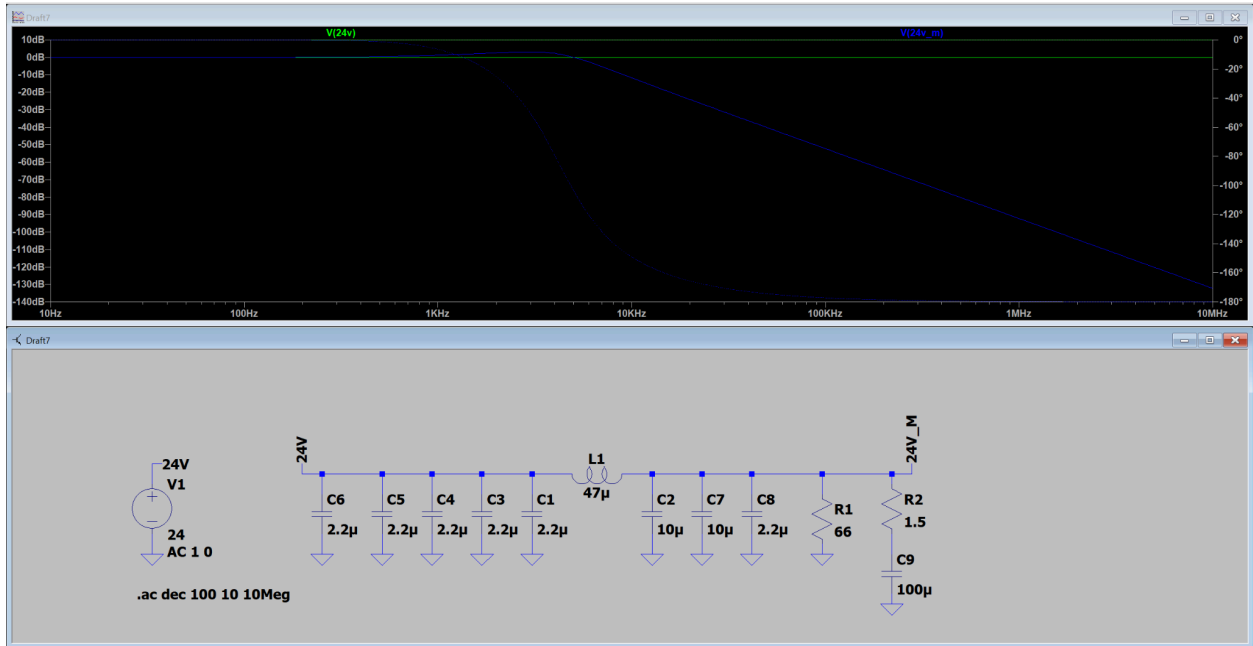
The power subsystem will be responsible for taking in 24V DC from an external power supply and serve as the main point of power conversion, distribution, and filtering within the PCB. There are two main loads on the 24V rail being the 24V inverter stage for controlling the two brushless DC motors and the 24V to 5V buck converter and its downstream loads. The 24V input should have proper capacitance for switching relatively higher power inductive loads like the two motors as well as a PI filter to prevent switching noise from the inverter from propagating back onto the 24V bus and into sensitive analog signals. The 24V rail should also have a schottky diode for reverse battery protection and a TVS diode for ESD protection. In addition to the 24V to 5V buck converter to generate a 5V rail, there will also be a 5V to 3.3V LDO for IC and microcontroller power. Depending on noise seen on the 3.3V rail, there may be a ferrite bead added to filter noise before feeding any reference voltages on the microcontroller.

Calculations for power design

POWER DESIGN				
3V3 Rail	typ	max	unit	notes
STM32H7432ZIT6		0.62	A	
DRV8304		0.005	A	
DRV8304		0.005	A	
TCAN1044AVDRQ1		0.13	A	
LAN8742A-CZ		0.06	A	
Pull ups		0.1	A	
Total 3V3 Current		0.92	A	max expected draw on 3.3V rail
Buffered 3V3 Current		1	A	buffered value
LDO Selection				5V0 to 3V3
Current		1	A	
Voltage drop		1.7	V	5-3.3v
Power dissipated		1.7	W	
RJtheta		40.4	C/W	
Ambient Temp	25			
Total Temp		93.68	C	
PN: LM1084ISX-3.3/NOPB				
5V Rail				
3V3 LDO, power		3.3	W	3.3 power draw
3V3 LDO, Ido loss		1.7	W	3.3 Ido dissipated
3V3 LDO, 5V input		5	W	draw on 5V rail
3V3 LDO, 5V input current		1	A	current into 3.3V Ido
TCAN1033AVdrQ1		0.13	A	
Total 5V Current		1.13	A	
Buffered 5V Current		1.5	A	
24V to 5V Buck				
5V Current draw		1.5	A	
5V Power		7.5	W	
Buck Efficiency		0.863		
Input power		8.691	W	
24V Current to non motor		0.362	A	

PI Filter Simulation

In order to filter out switching noise from the inverter and prevent it from propagating back onto the 24V rail which feeds the rest of the PCB, a PI filter is used. Below shows an LTSpice simulation which sweeps frequencies at 24V and shows attenuation before the expected switching frequency of the inverter of 25kHz.



2.2.2 Microcontroller

The microcontroller subsystem contains the microcontroller to run firmware and control the PCB, a flashing connector, a non-volatile memory IC, and some auxiliary buttons and potentiometers. The microcontroller subsystem interfaces with all other subsystems being the vision, communications, power, and motor + motor controls subsystems. The microcontroller will run the pcb state machine, controlling information flow, commanding the motor driver via PWM controls, and taking in 3.3V power from the power subsystem. The flashing connector is for uploading firmware to the microcontroller and debugging, the non-volatile memory IC is for storing motor position and calibration data, the auxiliary buttons are for boot modes and reset, and the potentiometer will be for initial testing of the motors for speed or position control without the communications in the loop.

Calculations and Design for Crystal Oscillator

Crystal Oscillator Design		
PN: ABM11W-25.0000MHZ -6-D2X-T3		
	Value	Note
CL1	10	pF
CL2	10	pF
Cs	3	pF
CL	8	
Gm_crit_max	1.5	mA/V
ESR	30	
2*pi*F	157079632.7	
C0	1.00E-12	
CL	6.00E-12	
gmcrit	0.000145083184	
gmcrit_mA	0.1450831847	
Gain Margin	10.33889629	>5 so ok

*Referenced STM32 Application Note AN2867 for crystal oscillator design parameters

*Referenced STM32 Application Note AN4938 for Microcontroller schematic setup, i.e. decoupling capacitor scheme & auxiliary pin setup

2.2.3 Communications

The communications subsystem is responsible for converting board-level information into a protocol suitable for longer distance and protected against any incoming interference and interfacing with the laptop which runs the vision and will command the PCB to move the motors to a certain position. The communications subsystem currently consists of both ethernet and CAN protocol hardware. The CAN hardware serves as a backup in case the ethernet hardware is not successful. Ethernet could enable higher bandwidth and lower latency in the system. The communications subsystem interfaces between the microcontroller and vision subsystems.

*Referenced LAN8742 Schematic checklist Application Note for LAN8742 Ethernet Physical layer schematic setup and LAN8742 Placement and Routing Checklist Application Note for layout design

2.2.4 Motor + Motor Controls

The Motor + Motor controls subsystem is responsible for converting DC input from the power subsystem into AC signals to control the external motors which will drive the position of the camera for vision tracking. The subsystem consists of a smart gate driver, inverter stage, and several sensing circuits: phase voltage and current, inverter temperature, dc-link voltage and current, as well as an encoder interface

for mechanical position tracking of the motors. The subsystem interfaces with the microcontroller which sends inputs for the gate driver and takes in analog signals from the sensing circuits and I2C from the motor encoder to create a closed-loop feedback system.

Inverter Stage Component Selection and Design

Inverter Design				Assumption/Configurable
Switching FETs Selection	SIS890ADN			Calculation
				SPI REG SET VALUE
	typ	max	unit	notes
Assumptions				
Bus Voltage	24		V	
Drive PWM, fPWM	25000		Hz	
Sensored FOC				
Peak phase current	4		A	
Motor winding resistance	4.8		Ω	
Bus voltage	24		V	
Max Motor Current Calc	5		A	
Max Current Design Ref	7		A	
Gate Drive Voltage	10		V	
DRIVE CURRENT CALCS	typ	max	unit	notes
Gate charge, Qg	1.92E-08	2.90E-08	C	total amount of charge required to turn a MOSTFET fully on charge during miller plateau
Miller charge, Qdg	2.10E-09		nC	
Sinusoidal Commutation, IVCP	1.44E-03	2.18E-03	A	Charge Pump Capacity
IDRIVE	1.50E-02		A	Looks good, only uses 14% of drive current capacity
Turn on target, tr	1.50E-07		s	
Turn off target, tf	1.00E-07		s	
IDRIVEP, min	1.40E-02		A	
IDRIVEN, min	2.10E-02		A	
IDRIVEP	1.50E-02		A	
IDRIVEN	3.00E-02		A	

POWER LOSS CALCS	typ	max	unit	notes
Stall conduction				
rds(on)	0.021	0.0255	Ω	
rjtheta	26	34	C/W	
p_dissipated	0.525	0.6375	W	conduction loss
Switching loss				
Vbus	24		V	
Max Current	4		A	
tr	1.50E-07		s	
tf	1.00E-07		s	
fPWM	25000		Hz	
Psw	0.30		W	switching loss
Ploss,tot	0.83	0.94	W	conduction + switching losses
ambient temp	25		C	
junction temp	46.45	56.88	C	not crazy temp rise, looks okay at projected stall per fet
PHASE CURRENT SIZE	typ	max	unit	notes
Vref	3.3		V	analog ref voltage
Gain	20		V/V	5, 10, 20, 40 V/V
VO	1.4		V	output dynamic range
Max Current	5		A	
Shunt Resistor	0.014		Ω	select 14 mΩ shunt res, >0.5W
Pres	0.35		W	power dissipated, reference for wattage rating

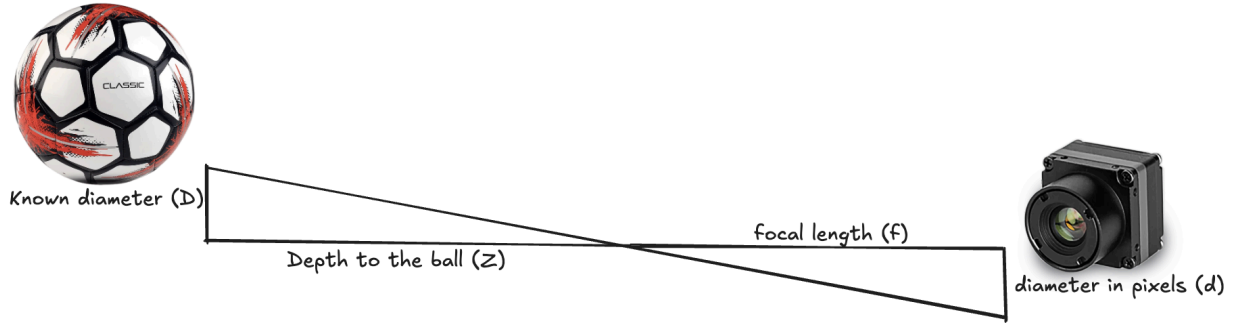
*Referenced DRV8304 Datasheet for design parameters and equations

2.2.5 Vision

The vision detection model is responsible for detecting the ball and providing a bounding box, then using camera intrinsic/extrinsic matrices to map from pixel coordinates to real world coordinates. These real world coordinates will then map to positional information which will be fed to the PCB from the laptop. In order to map pixel coordinates to real world coordinates, we have an option to either use different methods of pose estimation models due the monocular vision constraint, or to estimate the depth based on the proportion between how many pixels the ball takes up on the screen versus the actual diameter of the ball.

The first requirement is camera calibration in order to get the camera's intrinsic matrix. The intrinsic matrix describes the camera's focal lengths and principal points (in x and y). The easiest way to do a full camera calibration is to use [OpenCV's camera calibration library](#), which captures images at different tilts and positions, uses a checkerboard to estimate the intrinsic matrix and lens-distortion coefficients. This is important primarily because we're working with a moving object, and the [camera](#) that we're using uses rolling shutter. The way rolling shutter works is that it goes line by line or column by column when capturing the image, versus global shutter, which takes the entire image at once. Due to the nature of how a fast-moving object is captured with rolling shutter, there may be distortion when capturing a moving object which will result in the object looking more oval-like. However, we can use OpenCV's camera calibration library to account for this, as the matrix is able to account for these distortion effects that we get from using our camera.

Shown below is a figure detailing the math that we can use through simple geometry to calculate the actual depth from the camera to the ball. After camera calibration, we will know the focal length of the camera. Then, because we can “cheat” and know the actual diameter of the physical soccer ball, we can use these two, along with the diameter in pixels, to calculate the depth to the ball by using the equation $Z = f \frac{D}{d}$, where D is the diameter of the physical ball, d is the diameter in pixels, and f is the focal length.



After calculating Z , which is the depth, we can use this to calculate the actual real-world X and Y coordinates, which we will send to the motor controller. Deriving the equation for this is fairly similar to how we calculated Z , where we use similar geometry to get to $u = f_x \frac{X}{Z}$ and $v = f_y \frac{Y}{Z}$, where u and v are the horizontal and vertical pixel coordinates, Z is the real-world depth value, f is the focal length, and X and Y are real-world horizontal and vertical coordinates. Then, one important thing is that the displacement is measured from the optical axis. However, image coordinates usually start at the top-left corner. Therefore, from our camera calibration, we also have two values, C_x and C_y , which are the x and y principal points (or offsets). We can use these offsets to get a final equation of $u = f_x \frac{X}{Z} + C_x$ and $v = f_y \frac{Y}{Z} + C_y$. Then, we can solve for X and Y , and our final equations for finding X and Y are $X = \frac{Z(u - C_x)}{f_x}$ and $Y = \frac{Z(v - C_y)}{f_y}$. Our motor takes in position coordinates relative to its origin, which means that we must feed it an offset of coordinates relative to its origin.

2.3 Subsystem Requirements

2.3.1 Power

High level requirement: Reliably deliver power to downstream loads; successful power conversion (24V, 5V, 3.3V rails), filtering, and capacitance design.

Design Contribution: The Power subsystem allows the PCB responsible for motor controls to be powered reliably and for the camera to constantly be tracking the soccer ball.

Interfaces: The Power subsystem interfaces with the microcontroller and communications subsystems via 3.3V and 5V rails, and the motor and motor controls subsystem via 3.3V, 5V, and 24V rails.

R&V

Requirement	Verification
The power subsystem should have reverse battery protection up to -50V	Apply -50V from VIN to GND using a power supply, ensure system still functioning after event
The power subsystem should supply at least 1A of current on the 3.3V rail with 5% tolerance	Use multimeter on DCV setting to probe 3.3V rail while PCB is turned on, use a breadboard with load resistors or electronic load to draw power on 3.3V rail
The power subsystem should supply at least 1.13A of current on the 5V rail with 5% tolerance	Use multimeter on DCV setting to probe 5V rail while PCB is turned on, use a breadboard with load resistors or electronic load to draw power on 5V rail
The power subsystem should support at least 8A of current on the 24V rail with 5% tolerance	Use multimeter on DCV setting to probe 24V rail while PCB is turned on, use a breadboard with load resistors or electronic load to draw power on 24V rail
The power subsystem should have a layout with polygons and traces sized to prevent >75C temperature rise from ambient temperature	During a stall condition of the motor or high current draw on the 24V AC path, confirm components don't exceed temperature rise using thermal camera

2.3.2 Motor and Motor Controls

High level requirement: Control the two-axis motors with enough precision (within 5% accuracy) and response to meet object tracking requirements (run a ~20kHz control loop)

Design contribution: The motor and motor controls subsystem allows the system to move the camera's intended field of view to keep the soccer ball within our specified window. The control loop of the motors will also contribute to the gimbal position frequency.

Interfaces: The motor and motor controls subsystem interfaces with the microcontroller subsystem via 6 PWM signals, a SPI interface, and 3 analog signals for phase current sensing.

R&V

Requirement	Verification
The subsystem must have inverter MOSFETs sized for 6A continuous current draw with less than a 75C temperature rise above ambient temperature	During motor stall event, and during initial bring-up, verify with thermal camera and current clamp that PCB is not exceeding maximum temperature rise in higher power conditions
The subsystem must position each gimbal independently with less than 5% error of each axis' operating ranges	Use potentiometers on PCB as interface to control motors, use physical markings on mechanical assembly and position feedback to verify accuracy
The subsystem should accept and process new position commands at $\geq 5\text{Hz}$	PCB main loop should finish executing fast enough to accept new position command from the laptop, can just log timestamps of each main loop execution
The subsystem should provide three phase current measurement, three phase voltage measurement, inverter temperature, and motor encoder position feedback for closed-loop control of each motor	Use breakpoints in firmware dev and telemetry messages to confirm that phase current, phase voltage, inverter temperature, and position feedback are present. All signals are analog voltages with expected values which can be initially verified during bring-up via a multimeter at the ADC pin.

2.3.3 Communications (Laptop to PCB)

High level requirement: Relay information with low latency ($\sim 5\text{ms}$) between the microcontroller and laptop.

Design Contribution: The firmware converts board level logic into a differential, transformer-isolated physical layer suitable for a multi-meter cable run. It carries tracking error from the laptop to the STM32H743 on the PCB, and returns telemetry in the reverse direction.

Interfaces: The Communications subsystem interfaces with the Vision and Microcontroller subsystems via differential CAN or Ethernet MDI and either CAN Tx/Rx or Ethernet MII.

Requirements

R&V

Requirement	Verification
The subsystem must deliver tracking commands from the laptop to the microcontroller with latency of <5 ms	Send many timestamped commands from the laptop and have the MCU echo each one back. Measure round trip time on the laptop, and divide it by half to get one way latency. Make sure latency is less than 5ms for 99% of messages.
The subsystem must transmit tracking commands to the microcontroller and return motor position, operating status, and fault telemetry to the laptop	Run a long session sending continuous commands, log all telemetry on the laptop. Trigger fault condition and confirm telemetry has no gaps and fault is properly reported.
The subsystem must detect and reject messages that fail the selected protocol integrity checks and prevent rejected messages from being applied as motor commands	Send messages with errors such as wrong length, out of range setpoints, invalid sequence, etc. from the laptop and confirm that the reject counter for the MCU matches the number sent and the motor position doesn't change.
Ethernet ≥ 1 Mbps (or CAN FD ≥ 1 Mbps)	Use USB to ethernet dongle and ethernet cable between laptop and PCB to confirm data rates by sending dummy messages. Use USB to CAN to confirm data rates by sending dummy messages.

2.3.4 Microcontroller

High level requirement: Control the pcb; Run state machine, motor control loop, communicate with laptop for position information. The entire loop should run in under 200 ms to match the speed of the ball.

Design Contribution: The microcontroller converts the tracking error received from the laptop into an axis position using the camera, then closes the position and current loops against the encoder.

Interfaces: The microcontroller subsystem interfaces with the power, motor and motor controls, and communications subsystem. It should be able to Tx/Rx to the communications subsystem over RMII. It will interact with the motor and motor controls subsystem by outputting six complementary PWM signals. From the power subsystem it takes 3.3V for VDD.

Requirements

R&V

Requirement	Verification
The selected microcontroller should have an Ethernet MAC and CAN FD peripherals	Confirmed by the datasheet. The STM32H743 has a 10/100 Ethernet MAC and 2x FDCAN

The selected microcontroller should have >2 SPI channels, 1x I2C, >16 ADC inputs, and high speed timer channels specifically for motor controls	Confirmed by the datasheet. Build full pin assignment in STM32CubeMX and check that it has no conflicts
The microcontroller must generate six complementary PWM signals at 20 kHz with at least 10 bits of duty resolution and hardware dead-time insertion to prevent shoot-through on the inverter half-bridges	Use oscilloscope and gate driver input testpoints to verify complementary switching output, switching frequency, and deadtime insertion
The microcontroller must read the AS5600 angle register over I2C at 400 kHz and update the position loop at a minimum of 1 kHz, nested inside the 20 kHz current loop	Use breakpoints during bring-up to verify the correct registers are read in the AS5600 and values are abstracted in firmware successfully
The microcontroller must store encoder zero offsets and calibration constants in non-volatile memory and validate them by checksum on boot	Verify during bring-up that can set and readback calibration values after a power cycle, potentially readout over ethernet for ease of validation

2.3.5 Vision

High level requirement: Detect the ball and produce a gimbal position command from each frame, with total latency from image capture to command transmission under 65ms.

Design Contribution: The vision subsystem has to capture frames from the camera, detect the ball, and compute the offset between the ball's bounding-box center and the camera frame center. This is the part that makes the system autonomous.

Interfaces: The vision subsystem interfaces with the PCB subsystem via a USB connection to relay position commands from the laptop to the PCB and motor feedback and telemetry information from the PCB to the laptop.

Requirements

- Detection Inference: Detect object with >95% accuracy at 30 FPS within 50 ms of inference latency
- Preprocessing and Postprocessing: Image pre and post processing should be less than 10 ms
- Communication (Camera to Laptop): Gimbal positional movement information latency should be < 5ms when communicating from the laptop to PCB via ethernet.

R&V

Requirement	Verification	Note
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The detection mechanism must have an intersection-over-union (IoU) > 0.5, and it must achieve > 95% precision while processing each image.	At least 50 images will be collected across different distances, ball positions, and backgrounds. The labeled dataset will be used to calculate accuracy on predicted classification tasks by the model.	IoU will be calculated by taking the area of prediction and intersecting it with the area of the ground-truth bounding box, then dividing that by the union of the predicted and ground-truth bounding boxes.
The full end-to-end latency of pre-processing, inference, and post-processing must take less than 5 ms on a single image.	The system will use timestamps to measure inference latency along with pre/post-processing latency.	Pre-processing and post-processing will primarily be done on the CPU for tasks such as NMS, while inference will be entirely done on the GPU. Given our hardware and the size of the model we're using, this should take less than 5 ms. If not, there may be issues such as low GPU utilization, blocking code, etc.

2.4 Tolerance Analysis

Assuming a 640x480 image resolution at 30 FPS, the YOLOv26 object detection is running on an Intel Core Ultra 7 16 Core, which is estimated to run inference and postprocessing in around 20 ms with around a 10 ms latency from the camera through USB to the laptop. From the laptop to the MCU via ethernet, there's an estimated 2-3 ms of latency with around 20 ms of latency for the motor to receive and start moving from the data. Furthermore, there should be around a 10-15ms delay to account for additional latency bottlenecks such as waiting for frames or having an idle CPU throughput. In total, this accumulates to roughly 65 ms from image capture to visible gimbal response. This is significantly faster than our required baseline for around 200ms. However, for us to be able to capture a soccer rally well we should assume the ball is traveling at around 4 m/s, which roughly corresponds to around 75 ms in latency. With 65 ms as a minimum and not fully being conservative, it can easily exceed this 75 ms threshold. Therefore, a primary bottleneck in this is the image capturing and image detection stage where the CPU isn't fully streaming data as efficiently as possible. To address this, we can avoid using YOLOv26 model detection as a whole, and entirely rely on classical computer vision techniques such as contour detection where we can base it off of recognizing a circular white or yellow object, which would run in only a few ms.

3. Cost & Schedule

3.1 Cost

Labor

Discipline	Hourly (\$)	Hours	Total (\$)
Software	60	200	12,000
Firmware	50	150	7,500
Hardware	40	200	8,000
Mechanical	30	50	1,500

Parts

i. PCB Components

Comment	Description	Designator	Footprint	LibRef	Quantity	Unit cost (USD)	1x board cost (USD)	3x board cost (USD)
GRM188R61E475KE15	Capacitor	C1	CAPC1608X90N	GRM188R61E475KE15	1	Unpriced	Unpriced	Unpriced
C0402C104K4RACTU	Capacitor	C2, C3, C4, C5, C6, C7	C0402C104K4RACTU	C0402C104K4RACTU	37	\$0.05690	\$2.11	\$6.32
C1005X5R1E105K050B	Capacitor	C14, C44, I 0, C44, I 1	CAPC1005X55N	C1005X5R1E105K050B	7	\$0.05400	\$0.38	\$1.13
GJM1555C1H5R68B01	Capacitor	C17, C18	CAPC1005X55N	GJM1555C1H5R68B01	2	\$0.11000	\$0.22	\$0.66
08055C103KAT2A	Capacitor	C22	CAPC2012X94N	08055C103KAT2A	1	\$0.10000	\$0.10	\$0.30
C3225X7R1H106M250	Capacitor	C23, C24, C29, C30, C31	CAPC3225X230N	C3225X7R1H106M250	6	\$0.67300	\$4.04	\$12.11
MSASU21GSB7105KTN	Capacitor	C25, C34, C86, I 0, C86	CAPC2012X135N	MSASU21GSB7105KTN	8	\$0.11300	\$0.90	\$2.71
10TPB47M	Capacitor Polarised	C26	16TDC33MYFB	10TPB47M	1	\$1.42000	\$1.42	\$4.26
TAJA106K016RNJV	Capacitor Polarised	C27, C28	CAPPM3216X180N	TAJA106K016RNJV	2	\$0.55000	\$1.10	\$3.30
865060653010	Capacitor Polarised	C31	CAPAE830X1050N	865060653010	1	\$0.68000	\$0.68	\$2.04
GRM1555C1H102JA01	Capacitor	C36, C37, C38, C39, C40	CAPC1005X70N	GRM1555C1H102JA01	12	\$0.03200	\$0.38	\$1.15
EMVE101ARA101MKE0	Capacitor Polarised	C43, I 0, C43, I 1	CAPAE1300X1380N	EMVE101ARA101MKE0	2	\$1.64000	\$3.28	\$9.84
C0603C223K1RACTU	Capacitor	C50, I 0, C50, I 1	C0603	C0603C223K1RACTU	2	\$0.10000	\$0.20	\$0.60
GCM1885C2A331JA16	Capacitor	C51, I 0, C51, I 1, C52	CAPC1608X90N	GCM1885C2A331JA16	12	\$0.05900	\$0.71	\$2.12
GRM1555C1H100FA01	SMD Capacitor C0G(E	C57, C62	CAPC1005X55N	GRM1555C1H100FA01	2	\$0.11000	\$0.22	\$0.66
C1005X7S2A103K050B	Capacitor	C58, I 0, C58, I 1, C59	CAPC1005X55N	C1005X7S2A103K050B	7	\$0.07800	\$0.55	\$1.64
CL10A106MA8NRNC	Capacitor	C69	CAPC1608X90N	CL10A106MA8NRNC	1	\$0.34000	\$0.34	\$1.02
GRM1555C1H471JA01	Capacitor	C74	GRM15x	GRM1555C1H471JA01	1	\$0.10000	\$0.10	\$0.30
GRT188R61H225KE136	Capacitor	C79, C80	CAPC1608X90N	GRT188R61H225KE136	2	\$0.19000	\$0.38	\$1.14
GRM188R72A104KA35	Capacitor	C82, I 0, C82, I 1	GRM18x	GRM188R72A104KA35	2	\$0.16000	\$0.32	\$0.96
PESD1CAN_215	Bi-Directional ESD protect	D1	SOT95P230X110-3N	PESD1CAN_215	1	\$0.54000	\$0.54	\$1.62
B340LB-13-F	Schottky Diode	D2	D10M5336X250N	B340LB-13-F	1	\$0.75000	\$0.75	\$2.25
FSV1060V	Schottky Diode	D3	FES10D	FSV1060V	1	\$1.98000	\$1.98	\$5.94
TVS2700DRVR	27V Flat-Clamp Surge	D4	SON6SP200X200X80-7	TVS2700DRVR	1	\$1.29000	\$1.29	\$3.87
BLM18AG601SN1D	Ferrite Bead	FB2	BLM18SP221SN1B	BLM18AG601SN1D	1	\$0.10000	\$0.10	\$0.30
RJM618D3B8K1ANR	1 Port RJ45 Through Ho	J1	RJM618D3B8K1ANR	RJM618D3B8K1ANR	1	\$5.40000	\$5.40	\$16.20
1729160	Connector	J2, J5	1729160	1729160	2	\$2.86000	\$5.72	\$17.16
1729131	Connector	J3, J4	1729131	1729131	2	\$1.44000	\$2.88	\$8.64
FTSH-105-01-L-DV-K	Samtec, FTSH, 10 Way	J6	FTSH10501LDVK	FTSH-105-01-L-DV-K	1	\$1.37000	\$1.37	\$4.11
SDR1307-220ML	Inductor	L1	SDR1307270ML	SDR1307-220ML	1	\$0.94000	\$0.94	\$2.82
SRR1260-470M	Inductor	L2	SRR1260470M	SRR1260-470M	1	\$1.05000	\$1.05	\$3.15
LTST-C193T8KT-5A	LED	LED1, LED6, LED7, LED	LEDC1608X45N	LTST-C193T8KT-5A	4	\$0.15600	\$0.62	\$1.87
LTST-C191T8KT	LED	LED2, LED4, I 0, LED4	LEDC1608X55N	LTST-C191T8KT	3	\$0.15000	\$0.45	\$1.35
LTST-C191T8KT	LED	LED3, LED5, I 0, LED5	LEDC1608X55N	LTST-C191T8KT	3	\$0.15000	\$0.45	\$1.35
SIS890ADN-T1-GE3	N-CHANNEL 100-V(D	Q1, I 0, Q1, I 1, Q2, I 0	MOSFET_ODN-T1-GE3	SIS890ADN-T1-GE3	12	\$0.97100	\$11.65	\$34.96
BSS138P_215	MOSFET (N-Channel)	Q7, Q8, Q9, Q10, I 0, Q	SOT95P230X110-3N	BSS138P_215	7	\$0.12600	\$0.88	\$2.65
CRCW040233R0FKED	Resistor,Thick Film;33	R1, R41, R44, R45	RESC1005X40N	CRCW040233R0FKED	4	\$0.03200	\$0.13	\$0.38
RMCF1206J120R	120 Ohms A±5% 0.25W	R2	RESC3216X70N	RMCF1206J120R	1	\$0.10000	\$0.10	\$0.30
ESR10E2PJ1R5	Resistor	R3	RESC2012X65N	ESR10E2PJ1R5	1	\$0.15000	\$0.15	\$0.45
RMCF1206ZTOR00	Resistor	R4	RESC3216X70N	RMCF1206ZTOR00	1	\$0.10000	\$0.10	\$0.30
ERJ-2GE0R00X	Series/Type: Thick Film	R5, R6, R7, R8, R9, R14	RES_ERJ-2GE0R00X	ERJ-2GE0R00X	34	\$0.00950	\$0.32	\$0.97
CMP-009-00108-1	5K6 0.063W 5% 0402	R10, R23, R24, I 0, R24	RESC0402(1005)_L	CMP-009-00107-1	6	Unpriced	Unpriced	Unpriced
RMCF0402FT10K0	Description	R11, R42, R43, I 0, R43	STA_RMCF0402_STP	RMCF0402FT10K0	29	\$0.01140	\$0.33	\$0.99
RC0402FR-07120RL	120 Ohms A±1% 0.063W	R12, R13, R17, R18, R19	RESC1005X40N	RC0402FR-07120RL	12	\$0.01520	\$0.18	\$0.55
WSP1206R0140FEA	RES 0.014 OHM 1% 1W	R32, I 0, R32, I 1, R33	RESC3216X89N	WSP1206R0140FEA	6	\$0.73700	\$4.42	\$13.27
ERJ-P06J220V	Resistor	R35, I 0, R35, I 1, R36	ERJP06D1000V	ERJ-P06J220V	12	\$0.05000	\$0.60	\$1.80
ERJ3KF1003V	100 kOhms ±1% 0.1W, 220	R46, I 0, R46, I 1, R47	RESC1608X06N	CMP-055-000073-1	7	\$0.03900	\$0.27	\$0.82
PFR05S-221-FNH	220Ω, A±1%, 1/16W, 0.1	R56, R77, R101	RESC1005X40N	PFR05S-221-FNH	3	\$0.10000	\$0.30	\$0.90
RT0603BR07500RL	Resistor	R58	RESC1608X55N	RT0603BR07500RL	1	\$0.25000	\$0.25	\$0.75
ERJ-2RK220X1	Resistor	R64, R65, R68, R81, R8	ERJ2RKD1004X	ERJ-2RK220X1	7	\$0.03100	\$0.22	\$0.65
RC0402FR-0749R9L	Yageo 49.9, 0402 (1005	R72, R73, R74, R75, R8	RESC1005X40N	RC0402FR-0749R9L	6	\$0.02100	\$0.13	\$0.38
RC0402FR-0712K1L	Res SMD 0402 12K1 1%	R76	RESC1005X40N	RC0402FR-0712K1L	1	\$0.10000	\$0.10	\$0.30
ERJ-P06J222V	Resistor	R78	ERJP06D1000V	ERJ-P06J222V	1	\$0.14000	\$0.14	\$0.42
NTCG104EF104FTDSX	Thermistor	RT1, I 0, RT1, I 1	THRMC1005X55N	NTCG104EF104FTDSX	2	\$0.09000	\$0.18	\$0.54
PTS645SM43SMTR92_L	Switch (4-Pin Push)	S1, S2, S3	PTS645SM43SMTR92L	PTS645SM43SMTR92_L	3	\$0.36000	\$1.08	\$3.24
5015	Test Point Micro Mini S	TP1, TP2, TP4, TP5, TP6,	KEYSTONE_5015	5015	33	\$0.33160	\$10.94	\$32.83
STM32H743ZI6	ARM® Cortex®-M7 ST	U1	QFP50P2200X2200X16	STM32H743ZI6	1	\$18.29000	\$18.29	\$54.87
TCAN1044AVDRQ1	CAN Interface IC Enhanc	U2	SOIC127P600X175-8N	TCAN1044AVDRQ1	1	\$1.05000	\$1.05	\$3.15
DRV8304SRHAR	Triple Half Bridge Moto	U3, I 0, U3, I 1	QFN50P600X600X100-	DRV8304SRHAR	2	\$2.85200	\$5.70	\$17.11
LM22676MRX-5.0_NOR	SIMPLE SWITCHER 4.5V	U4	SOIC127P600X170-9N	LM22676MRX-5.0_NOR	1	\$5.50000	\$5.50	\$16.50
LM1084ISX-3.3/NOPB	5.5-A, 29-V, linear volta	U5	TO254P1524X463-4N	LM1084ISX-3.3/NOPB	1	\$3.30000	\$3.30	\$9.90
R-78K5.0-2.0	2.0 Amp SIP3 Single Out	U6	R78K5020	R-78K5.0-2.0	1	\$5.93000	\$5.93	\$17.79
TLV9004IPWR	4-Channel, 1MHz, RRIO	U7, U8, U9, U10, U12	SOP65P640X120-14N	TLV9004IPWR	5	\$0.60500	\$3.03	\$9.08
24LC168T-I_OT	16K, 2K X 8 2.5V Serial R	U13	SOT95P270X145-5N	24LC168T-I_OT	1	\$0.37000	\$0.37	\$1.11
LAN8742A-CZ	Microchip LAN8742A-C	U14	QFN50P400X400X100-	LAN8742A-CZ	1	\$1.53000	\$1.53	\$4.59
P090S-04F20BR10K	Variable Resistor	VR1, VR2	P090S04F20BR10K	P090S-04F20BR10K	2	\$1.86000	\$3.72	\$11.16
ABM11W-25.0000MHZ	25 MHz A±20ppm Cryst	Y1	XTAL_ABM11W-25.0000	ABM11W-25.0000MHZ	1	\$0.38000	\$0.38	\$1.14
ABM8W-25.0000MHZ	25 MHz A±10ppm Cryst	Y2	XTAL_ABM8W-25.0000	ABM8W-25.0000MHZ-4	1	\$0.53000	\$0.53	\$1.59

ii. Non PCB Components

Part	Manufacturer	Cost	Quantity	Total Cost
Motors	DFRobot	\$30	2	\$60
Camera	NBPower	\$32.76	1	\$32.76
USB to Ethernet				

iii. Non-Standard Parts

Part
Power Supply
Oscilloscope
Multimeter
SWD Flasher + Adapter

3.2 Schedule

MILESTONES	9/13	9/20	9/27	10/4	10/11
CLASS	9/15 TA MEET 9/18 SOLDERING DUE 6 PM 9/18 PROPOSAL DUE	9/25 PCB REVIEW 9/25 TEAM CONTRACT	9/29 FIRST ORDER 10/2 DESIGN DOC 10/2 DES REV SIGNUP	10/8 2nd ORDER	10/16 3rd ORDER
HARDWARE	SCHEMATICS	LAYOUT	HIT FIRST ORDER		RECEIVE, BRINGUP, REWORKS
MECHANICAL	FIND 3D PRINT	REDESIGN 3D	REDESIGN 3D	PRINT MECH	TEST MOTOR MOUNT, ASSEMBLY
FIRMWARE	DRIVERS, DEVICE DEV	APP LAYER DEV	TEST ON COTS PARTS	TEST ON COTS PARTS	
SOFTWARE	VISION DESIGN	TESTING VISION MODELS	BUY CAMERA/CALIBRATE	TESTING WITH CAMERA	3D -> 2D VISION DETECTION
INTEGRATION	ORDER COTS PARTS	RECEIVE COTS	TEST FW	TEST FW/SW STATE MACHINE	HITL
OVERALL					- MOVE MOTOR with POT - MOVE MOTOR with CAN/ETH Command
MILESTONES	10/18	10/25	11/1	11/8	11/15
CLASS		10/29 4th ORDER			MOCK DEMO WEEK
HARDWARE	REDESIGN	HIT 4th ORDER?		RECEIVE REV 2, BRINGUP	
MECHANICAL	REDESIGN 3D	PRINT MECH	TEST MOTOR MOUNT, ASSEMBLY		
FIRMWARE					
SOFTWARE	VERIFY 3D VISION MAPPING	TEST 3D VISION LOGIC	TEST VISION WITH MOTOR	INTEGRATION WITH FIRMWARE	FINAL TESTING AND INTEGRATION
INTEGRATION	HITL			INTEGRATION	FINAL INTEGRATION
OVERALL				- MOVE MOTOR with CAN/ETH - MOVE MOTOR with Tracking	- MOVE MOTOR with Tracking - TRACK OBJECT
MILESTONES	11/22	11/29	12/6		
CLASS		DEMOS	12/9 FINAL PAPER		
HARDWARE					
MECHANICAL					
FIRMWARE					
SOFTWARE					
INTEGRATION					
OVERALL					

4. Discussion of Societal Impact, Engineering Standards, Ethics, and Safety Considerations

4.1 Positive Contribution

Our vision-guided gimbal tracks a moving soccer ball and estimates its distance using a single camera, which offers an affordable approach to automation when used inside the sports industry. Economically, using our simple approach of estimating the depth using the known size of the physical ball, we can reduce the need for additional depth sensors, making the design more accessible to schools and recreation centers. Environmentally, we will try to use as many off-the-shelf components as possible, which can minimize our footprint of producing unnecessary components. Socially and culturally, soccer is enjoyed across several communities, and it provides a familiar and accessible way to introduce robotics and computer vision. Globally, commonly available components make the design easier to replicate in

the case of schools or other organizations wanting to build our product. To support public safety and welfare, the design should include safe and secure mounting, a stop mechanism, a safe laser, and local on-device video processing to protect privacy.

4.2 Engineering Standards

IEEE 802.3: Ethernet communication between the laptop and control PCB. [IEEE 802.3-2022](#)

IEC 60825-1: Laser classification and safety requirements. [IEC](#)

IEC 62368-1: Relevant safety guidance for camera and computing electronics.

4.3 IEEE/ACM Code of Ethics

The code of ethics focus on public safety, honesty, privacy, and responsible engineering. For our ball-tracking gimbal, ethical concerns include eye injury from the laser, injury from moving components, and sensitive information being captured on the camera. We can address this by including laser restrictions, mechanical/electrical safeguards, and minimal video collection. In addition, we will ensure the video collection is done on-device to protect privacy and ensure it's never uploaded to the cloud. Furthermore, we will ensure to keep everything as accurate and well documented as possible to follow the course ethics guidelines.

4.4 Electrical and Mechanical Safety

As prescribed by the IEEE Code of Ethics, we prioritize public safety in our design. The system uses a Class 2 visible laser with a power below 1 mW, in compliance with ANSI Z136.1 and IEC 60825-1. The principles of Section 1 prevent the laser beam from being pointed at any person. Mechanical halts on the tilt mechanism stop the beam from dropping down to head position, and the firmware set limits play the same role. The choice of testing location is made with respect to specular reflections. The pinch components of the gimbal are managed according to standard scientific practice and the fault condition disables the motors. The camera images are printed only when a consent is given and deleted after the work is done; no face recognition is done.

4.5 Procedures for Safety Concerns

Before each test, we'll ensure the wiring and gimbal mount are fully secure and ensure that all mechanical and firmware motion limits are correct. Then, we will confirm that the stop mechanism immediately stops and disables both the motors and the laser. Testing will occur in an environment where there are no hazardous conditions, with a safe area to mount the gimbal and kick a soccer ball around. Furthermore, we will ensure that there are no bystanders being captured in the image frames, and that the laser will remain off during everything except for when it's testing. Finally, power will always be disconnected before mechanical or electrical changes to the system. All of these methods will provide protection against unintended motion, injuries, and laser exposure, and their verification will be documented before the demonstration.

5. References

- [1] T.-Y. Lin et al., “Microsoft COCO: Common Objects in Context,” in *Computer Vision—ECCV 2014*, Lecture Notes in Computer Science, vol. 8693, Springer, 2014, pp. 740–755. doi: 10.1007/978-3-319-10602-1_48. Available: https://doi.org/10.1007/978-3-319-10602-1_48
- [2] G. Jocher, A. Chaurasia, and J. Qiu, “Ultralytics YOLO Documentation,” Ultralytics. Available: <https://docs.ultralytics.com/>
- [3] G. Bradski, “The OpenCV Library,” *Dr. Dobb’s Journal of Software Tools*, 2000. Available: <https://opencv.org/>
- [4] Z. Zhang, “A Flexible New Technique for Camera Calibration,” *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 22, no. 11, pp. 1330–1334, 2000. doi: 10.1109/34.888718. Available: <https://doi.org/10.1109/34.888718>
- [5] OpenCV, “Camera Calibration,” *OpenCV Documentation*. Available: https://docs.opencv.org/4.x/dc/dbb/tutorial_py_calibration.html
- [6] SMSC, “Component Placement Checklist for the LAN8742, 24-pin QFN Package,” CC524365, rev. A, Sep. 12, 2012. Available: https://ww1.microchip.com/downloads/en/DeviceDoc/LAN8742_QFN_Rev_A_Placement_Checklist.pdf
- [7] SMSC, “Routing Checklist for the LAN8742, 24-pin QFN Package,” RC614947, rev. A, Sep. 13, 2012. Available: https://ww1.microchip.com/downloads/en/DeviceDoc/LAN8742_QFN_Rev_A_Routing_Checklist.pdf
- [8] STMicroelectronics, “STM32H742xI/G STM32H743xI/G: 32-bit Arm Cortex-M7 480MHz MCUs, up to 2MB flash, up to 1MB RAM, 46 com. and analog interfaces,” datasheet DS12110, rev. 11, Jan. 2026. Available: <https://www.st.com/resource/en/datasheet/stm32h743bi.pdf>
- [9] ams AG, “AS5600: 12-Bit Programmable Contactless Potentiometer,” datasheet, ver. 1-06, Jun. 20, 2018. Available: <https://look.ams-osram.com/m/7059eac7531a86fd/original/AS5600-DS000365.pdf>
- [10] LCSC Editor, “How to Select a MOSFET for Motor Control,” LCSC, May 13, 2026. Available: <https://www.lcsc.com/blog/how-to-select-a-mosfet-for-motor-control/>
- [11] Fairchild Semiconductor, “FTC03V455A1 3-Phase Inverter Automotive Power Module,” application note AN-4160, rev. 1.0.0, Nov. 8, 2013. Available: <https://www.onsemi.com/download/application-notes/pdf/an-4160.pdf>

[12] STMicroelectronics, “Getting started with STM32H74xI/G and STM32H75xI/G MCU hardware development,” application note AN4938, rev. 7, Oct. 2024. Available: https://www.st.com/resource/en/application_note/an4938-getting-started-with-stm32h74xig-and-stm32h75xig-mcu-hardware-development-stmicroelectronics.pdf

[13] STMicroelectronics, “Guidelines for oscillator design on STM8AF/AL/S and STM32 MCUs/MPUs,” application note AN2867, rev. 24, Feb. 2026. Available: https://www.st.com/resource/en/application_note/an2867-guidelines-for-oscillator-design-on-stm8afals-and-stm32-mcusmpus-stmicroelectronics.pdf

[14] Texas Instruments, “LM22676/-Q1 42 V, 3 A SIMPLE SWITCHER Step-Down Voltage Regulator with Features,” datasheet SNVS587L, rev. L, Nov. 2014. Available: <https://www.ti.com/lit/ds/symlink/lm22676.pdf>

[15] M. Sclocchi, “Input Filter Design for Switching Power Supplies,” National Semiconductor, application note SNVA538, 2010. Available: <https://www.ti.com/lit/snva538>