Pseudo GPS for Romi
Preliminary Design Review

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For Charlie Refvem

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Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as a fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is at risk for the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

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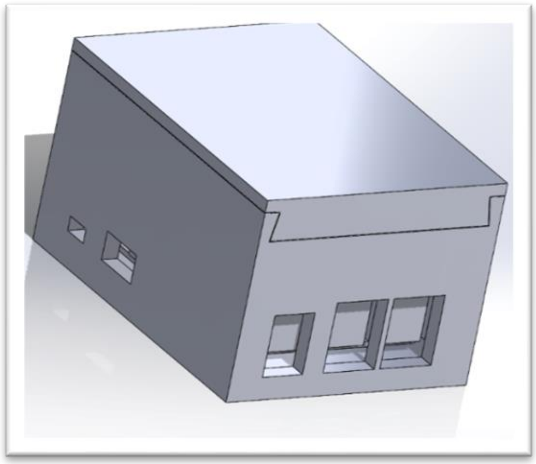
Four Panel Chart

Table 1. Four-Panel Chart for Preliminary Design Review

Project Overview	**Concept Description**
• Project Objective: Currently, the Romi robots used in the Mechatronics lab have no way of obtaining absolute orientation or location from onboard sensors. The Cal Poly ME 405 instructor, Charlie Refvem, and Mechatronics students need a way to deliver precise and real-time location data for multiple Romi robots for the development of better algorithms. Our aim is not just to improve tracking but also to enhance communication standards among multiple Romis by ensuring geolocation accuracy, precision, range, latency, and update rates. • GPS Prototype Goals: Provide precise, real-time location data for multiple mobile robots, improving tracking and communication standards. • Documentation and Impact: The project involves comprehensive documentation, including detailed electrical schematics and code explanations.	 The idea is that this housing will be able to house our Raspberry Pi 4, our camera, and any other components we would be using. Currently, our components like wires and Raspberry Pi would be within the box, while the camera sensor would be mounted on top of the housing. The housing includes hole cutouts that could be used for USB and power cables if they may need to be accessed. We ran a couple of tests with this prototype, such as placing our system overlooking a lab table and comparing where the best placement would be. From here, we would write code to detect the Romi bots once they start navigating the table.
Concept Justification	**What's Next**
The decision to integrate camera technology into the project is based on its accuracy, providing precise locational data within ±5mm. The Raspberry Pi camera's real-time data capabilities and fast update rate enable monitoring of multiple Romi robots. Additionally, the camera's cost-effectiveness and plentiful documentation online further supports its selection for enhancing tracking capabilities.	We will continue to develop our concept prototype, perform design analysis, and do a safety and failure mode effects analysis as the winter quarter ends. In the upcoming Spring quarter, we will generate a parts list and refine our model for the critical design review.

Overview

We have finalized the concept selection and are currently expanding further iterations on our concept prototype. This report aims to describe our chosen concept, our reasoning behind it, and a table of the alternate solutions considered. In addition, this report also includes a preliminary analysis, a weighted design matrix, an updated Gantt chart, a design hazard matrix, and our references. We hope to get feedback on our reasoning for the sensor choice and on the housing system.

Concept Description and Justification

Our decision to shift towards a camera-based tracking system stems from its effectiveness in meeting our project requirements. Cameras operate by exposing an imaging sensor to light for a brief period, and we can use the image captured to achieve our goal of delivering precise real-time location data for multiple Romis within the Mechatronics lab. For our hardware selection, we have opted to use the Adafruit Raspberry Pi High-Quality Camera with an M12 Lens mount as our primary sensor as shown in Table 1.

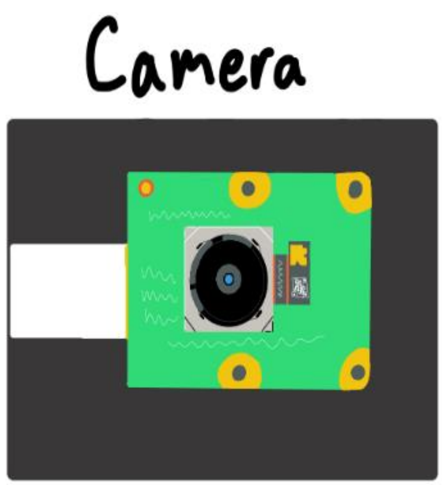


Figure 1. Adafruit Raspberry Pi High-Quality Camera with an M12 Lens

This camera offers adequate resolution, fits within our budget, and provides the flexibility of swappable lenses. Through the ribbon cable port on the Raspberry Pi 4, we can securely connect the camera to our existing microcontroller setup, while power can be conveniently supplied from a nearby outlet. As shown in Figure 2, the operational concept involves capturing images of the lab environment and processing them to create a grid representation of the table's surface, enabling precise categorization of Romis versus obstacles with a precision of ±5mm.

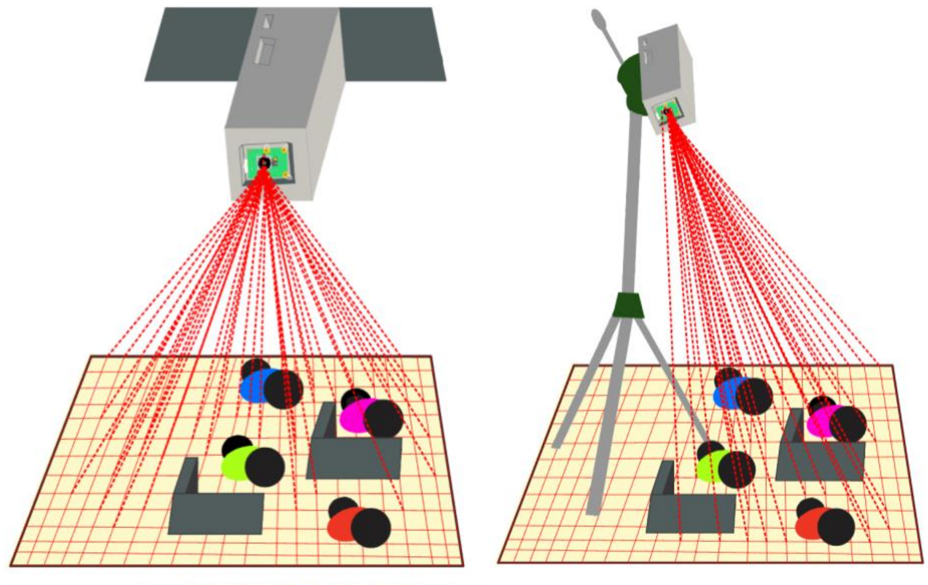


Figure 2. Tripod and ceiling-mounted configurations of the camera-based camera solution.

Mounted overhead, the camera captures images of the lab table, which are then processed to generate a grid overlay in 3-dimensional space, facilitating precise localization and differentiation of objects within the environment. This can be achieved by creating an origin point on the table and calibrate our system to measure the Romi bots and obstacles relative to it. As a result, we have two configurations for the Romis. The tripod configuration will be used primarily for testing code as it can be easily removeable in a lab environment. For the final product, we plan on creating a ceiling mounted configuration so it can be used for future classes. After creating an origin and grid representation, the camera continually monitors the movement of Romis and obstacles within its field of view, ensuring accurate detection and recording of any changes. The camera then sends this data, including the grid representation and object positions, to the microcontroller for processing. Through various algorithms, the microcontroller analyzes the data to categorize objects based on predefined characteristics and determines their relative locations with a precision of ±5mm. This process utilizes image processing techniques such as object recognition and spatial mapping to track and locate Romis and obstacles in real-time, ensuring that the tracking data remains current and reliable throughout the operation.

In summary, a camera-based tracking system effectively meets our project requirements by providing precise real-time location data for Romis in 3-dimensional space within the Mechatronics lab environment.

Alternative Solutions Table

Table 2. Alternative Solutions Considered

Solution Name	Description	Justification
Marvel Mind	 Indoor positioning and navigation system. Supports autonomous indoor navigation for mobile robots, vehicles, and drones.	Marvel Mind utilizes GPS technology in their Starter Set Super-MP-3D for precise indoor positioning and navigation, achieving an accuracy of ±2cm (about 0.79 in). By integrating multiple frequency options and IMU sensors, Marvel Mind enhances update rates and provides a versatile solution for autonomous indoor navigation of robots, surpassing the limitations of traditional ultra-wideband and BLE systems. We did not choose this as our solution solely based on the cost of the product.
Xbox Kinect	 Technology that sends waves that bounce off objects and return to the transducer upon detection. Also utilizes features from an optical camera at the same time.	The Xbox Kinect is an RGB color VGA video camera that also utilizes a depth sensor that uses infrared light for 3D imagery. This device can detect movements and can map a room. Another useful function is that it has a microphone that can be used for voice commands. We could also use it to map out the table for the Romi bots and detect their movements. We did not choose this as our solution because it couldn't get the precision of 5mm (about 0.2 in) that our sponsor was looking for.

GPS	 Technology that relies on satellite signals received by specialized receivers to triangulate an object's precise location.	GPS, or Global Positioning System, uses satellites to determine geolocation information. While commonly used, it lacks millimeter-precise tracking and indoor use can hamper the signal. The issue with GPS systems is that they would not give the exact location of the Romi bots on the table, GPS is good for giving general position.
Lidar	 Technology that employs laser pulses to measure distances by analyzing the reflection of light from objects.	This technology boasts high accuracy with a margin of ± 2mm. However, for large companies, the cost of 3D Lidar can exceed thousands of dollars. The limitation of Slamtec RPLIDAR A1 lies in its 2D scanning capability along a single plane.

Appendices

Preliminary analysis

In our concept prototype phase, our focus was on understanding the functionality of our solution. Utilizing a 3D printed housing and a tripod provided by one of our team members, we visualized the design of our solution as shown in Figure 3. Through this process, we recognized that employing a tripod design might necessitate the housing with sensors to pan back and forth to scan the entire table effectively as shown through Figure 4. The envisioned setup allows the camera to swing and cover the full length of the table, ensuring comprehensive scanning. Moreover, we acknowledged the significance of positioning our device appropriately.

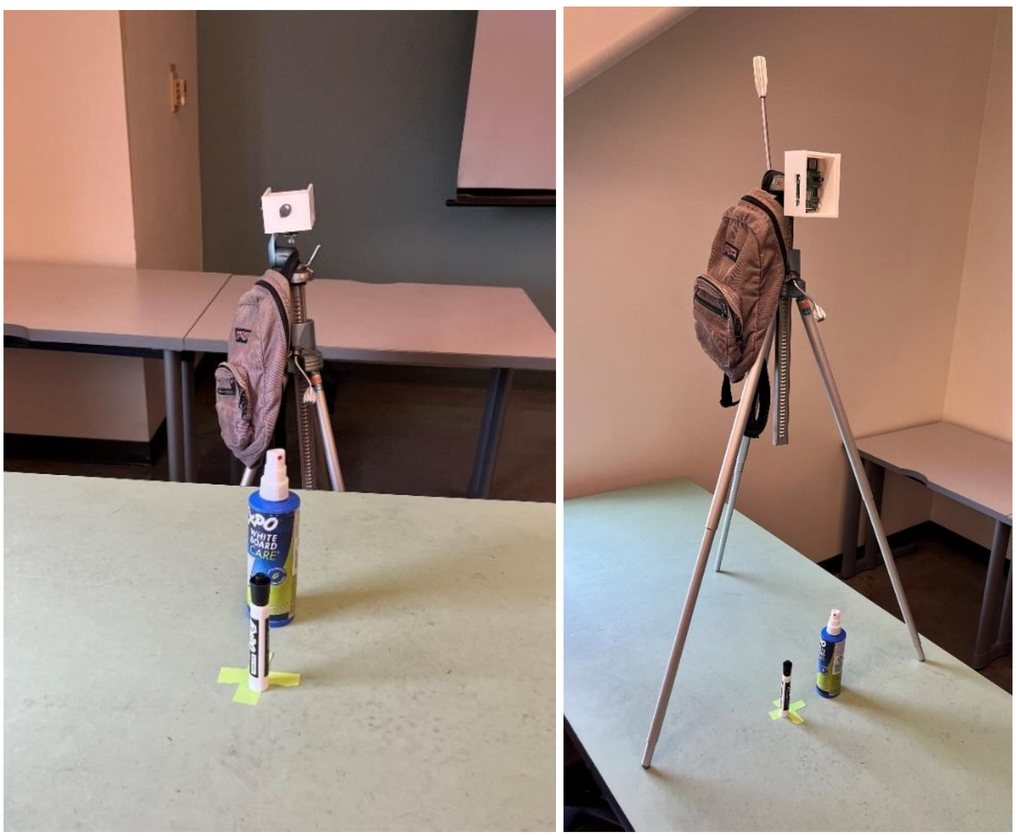


Figure 3. Demonstration of our housing overlooking a table from both a side view (left) and a top-down perspective (right), indicating potential limitations in object detection depending on their placements.

Figure 4. A demonstration of our housing overlooking the table from a side view. This view complements the insights gained from Figure 3, emphasizing the importance of device positioning for optimal scanning efficiency.

Also, if we continue using this specific tripod setup, we will have to consider seeing the legs on the table. We have also discussed possibly putting our housing higher vertically. For testing, we have been using a tripod, but our sponsor has given the okay to make this device ceiling-mounted or even wall-mounted. If we had the device ceiling mounted, then it would have a larger field of view and would no longer have to pan back and forth. To mount the device to the ceiling, what we would do is 3-D print a tile the size of one in the classroom to replace it. Since we would need to attach the device, we do not want to damage one of the tiles that is in the classroom. This would make it easier to get approval to have the device installed on the ceiling. Figure 5 showcases the second iteration of our housing.

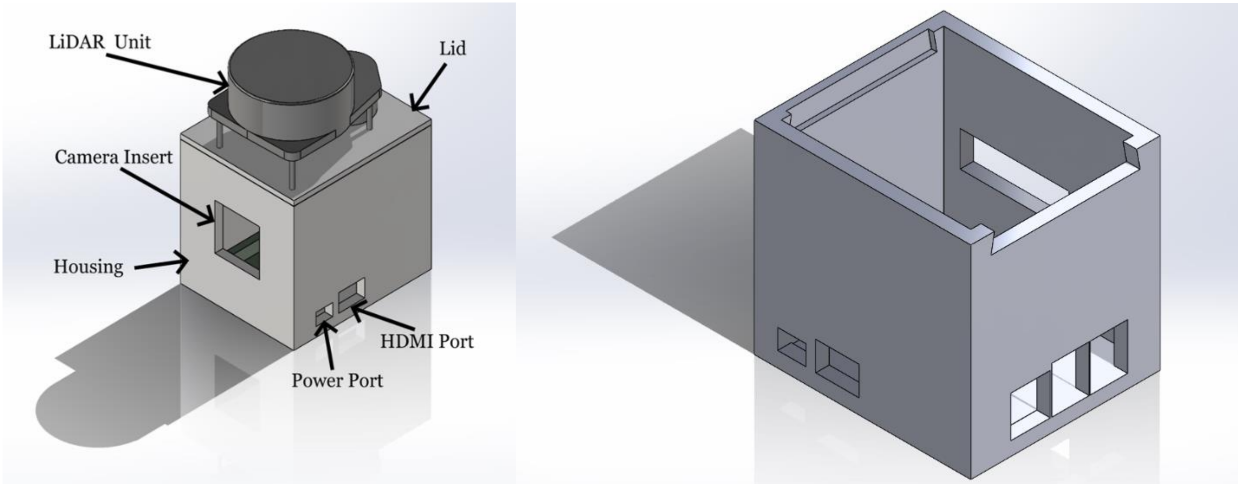


Figure 5. This is the second iteration of housing incorporating improvements based on insights gained from the initial print.

From designing this first housing, we gained a lot of insight on what to address in the next iteration. One such oversight was the failure to account for a breadboard, which will be necessary for developing the prototype and getting the Raspberry Pi to interface with the sensor attached. This can be remedied by making the housing larger by adding a slot for the breadboard to slide into. Another issue with this iteration is that the ports were made too small and should be fixed by making them much larger to account for cable limitations and not port limits. Another insight gained was that we could have a cutout on the front of the housing (where the lens is drawn) to accommodate a Raspberry Pi camera. As printing and iteration continue, we will continue to refine our solution based on the feedback we hear as well as adapting to any issues that may arise in the foreseeable future.

Following a meeting with our sponsor, it was brought to our attention that the previous SLAMTEC A1 LiDAR sensor is only capable of scanning in a 2D plane, which would mean that the sensor would have to be mounted on each individual Romi. This would not only not be able to obtain absolute positioning data but also vastly exceed budget. In lieu of LiDAR sensors, we will be focusing on a camera-based tracking solution, where the Romi robots will be tracked using image processing. Our project direction will be shifted to configuring our housing towards the Adafruit Raspberry Pi High-Quality Camera.

Initial analysis into using the camera as the tracking sensor seems favorable. In an ideal scenario where the camera is mounted to the roof and is perfectly centered over the table, we can calculate the viewing area from camera's field of view and mounting distance. Such a setup is depicted in Figure 6 below.

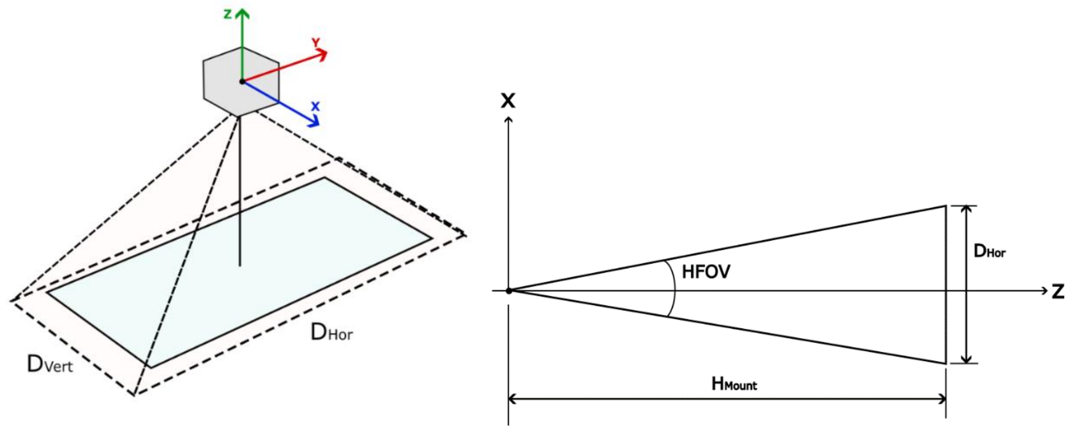


Figure 6. A 3D sketch of the camera set up above the table and its viewing area, and a 2D representation of the viewing area of the camera.

The viewing area of the camera can be thought of as a rectangle of sides D_{Hor} and D_{Vert} for horizontal and vertical distances respectively. We can find each side by taking a triangle of base (D) and height (H) with angle Field of View (FOV). We are given H_{Mount}, which is the distance of the camera above the table and FOV, which is given by the camera lens used. For example, let's solve for the horizontal distance D_{Hor}. We can break this down into a right triangle as shown in Figure 7 below.

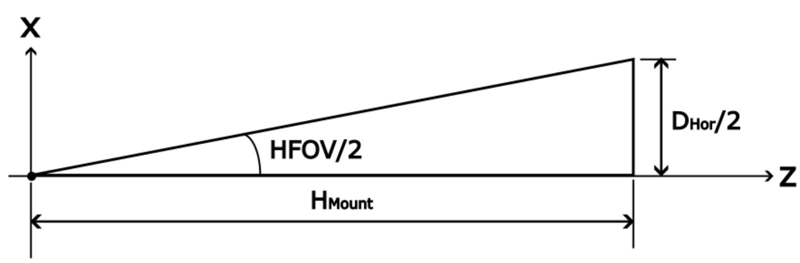


Figure 7. 2D View Triangle

Using trigonometry, we obtain

$$\tan\left(\frac{HFOV}{2}\right) = \frac{(D_{Hor}/2)}{(H_{mount})}$$

Rearranging the equation,

$$D_{Hor} = 2H_{mount}\tan\left(\frac{HFOV}{2}\right)$$

Solving for the vertical distance D_{Vert} follows a similar process, so similar equation can be used.

$$D_{Vert} = 2H_{mount} \tan\left(\frac{VFOV}{2}\right)$$

Using these two distances, we can calculate the viewing area of the camera.

$$A_{View} = D_{Hor} * D_{Vert}$$

Finally, by dividing viewing area by the pixel count, we can determine the area of each pixel in the image, which will be our tracking resolution area.

$$A_{pix} = \frac{A_{View}}{\# of Pixels}$$

A pixel is a square, so using the area of the pixel, we can determine the pixel width, which will be our tracking resolution.

$$W_{pix} = \sqrt{A_{pix}}$$

Idea List

Here is a full list of all ideas generated during our ideation phase.

- Swarm Intelligence optimization
- SLAM- Simultaneous Localization and mapping algorithms
- Topology-aware IMU fusion
- Collaborative Sensor fusion
- Dynamic Bayesian Network (DBN) Localizations
    - Uses IMU data w/ other sensor inputs to probabilistically estimate their loc.
- Acoustic Localization
- Reflective markers & Photodetectors
- IMU-based dead reckoning
- IMU w/ Bluetooth
- Ultrasonic sensors w/ IMU
- Sony Mocopi IMU
- Haritora Wireless IMU
- TAG Romi
- Force Romi
- HTC Vive trackers, SteamVR base stations (LiDAR)
- LiDAR (light detection & ranging)
- Computer vision of markers
- Wi-Fi Positioning system
- Bluetooth Beacons
- GPS w/ Bluetooth
- GPS module
- IR w/ IMU
- Infrared beacon tracking
- Neural-link Romi
- Romi Bar
- Train Romi
- Line-following Romi
- Augmented Reality (Pokémon GO style)
- Facial recognition tracking
- Camera (regular)
- Puck-based location
- Magnetic encoders
- Magnetic field sensors
- RFID (relative location to known reference points)
- Ping system (Like Skylanders RFID tags)
- Romi piloted by Xbox Controller (Sub Style)
- Computer Mouse-style tracking
- Xbox Kinect (motion detection)
- Xbox Kinect w/ IMU

- Disney Trackless systems
- Some guy shouting coordinates
- String-pulley positioning
- Laser Range Finders – w/ IMU
- Laser Pointer
- Coordinate Streaming Bluetooth
- Coordinate Streaming Ethernet cables
- Wi-Fi location?
- Scent beacons
- Star charts
- Coordinate Streaming Wi-fi
- Fire Tracking
- Temperature Tracking
- Thermal Tracking (NVG)
- Romi-Romi peer to peer coordinate streaming
- Twitch Stream Tracking
- Amazon Warehouse Robots

Weighted Design Matrix

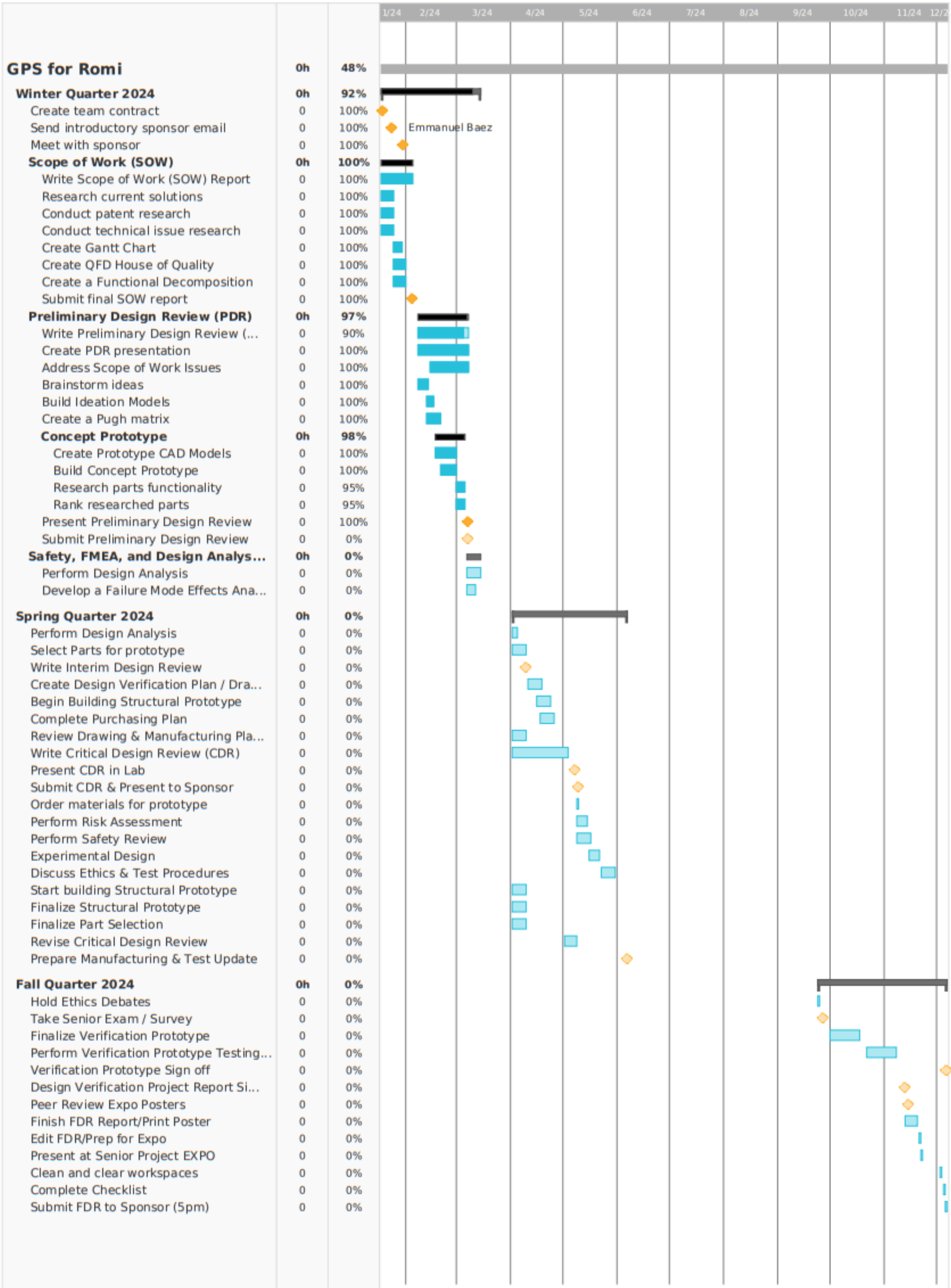
WEIGHTED
Decision Matrix

The Weighted Decision Matrix is a powerful quantitative technique that can be used to evaluate a set of choices against a set of criteria. It's an exceptionally useful tool that can come into play when you have to choose the best option and need to carefully consider a wide range of criteria.

CRITERIA	WEIGHTAGE	Marvelmind Tracker RATING	Marvelmind Tracker TOTAL	Xbox Kinect RATING	Xbox Kinect TOTAL	Regular Camera RATING	Regular Camera TOTAL	LIDAR RATING	LIDAR TOTAL	GPS RATING	GPS TOTAL
Cost	5%	2	2.00%	5	5.00%	4	4.00%	3	3.00%	4	4.00%
Accuracy	15%	3	9.00%	3	9.00%	3	9.00%	5	15.00%	3	9.00%
Precision	15%	3	9.00%	4	12.00%	3	9.00%	5	15.00%	4	12.00%
Range	10%	2	4.00%	3	6.00%	4	8.00%	3	6.00%	2	4.00%
Update Rate	15%	4	12.00%	4	12.00%	3	9.00%	5	15.00%	4	12.00%
Latency	15%	5	15.00%	3	9.00%	3	9.00%	5	15.00%	4	12.00%
Maintence	10%	4	8.00%	4	8.00%	4	8.00%	3	6.00%	3	6.00%
Ease of Integration	10%	4	8.00%	5	10.00%	5	10.00%	4	8.00%	3	6.00%
Weight	5%	5	5.00%	4	4.00%	4	4.00%	4	4.00%	3	3.00%

max	TOTAL Marvelmind Tracker	TOTAL Xbox Kinect	TOTAL Regular Camera	TOTAL LIDAR	TOTAL GPS
100%	72.00%	75.00%	70.00%	87.00%	68.00%

Up to date Gantt Chart



Design Hazard Matrix

Y	N	
	N	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	N	2. Can any part of the design undergo high acceleration/deceleration?
	N	3. Will the system have any large moving masses or large forces?
	N	4. Will the system produce a projectile?
Y		5. Would it be possible for the system to fall under gravity creating injury?
	N	6. Will a user be exposed to overhanging weights as part of the design?
	N	7. Will the system have any sharp edges?
	N	8. Will any part of the electrical systems not be grounded?
Y		9. Will there be any large batteries or electrical voltage in the system above 40 V?
	N	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	N	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	N	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	N	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	N	14. Can the system generate high levels of noise?
	N	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	N	16. Is it possible for the system to be used in an unsafe manner?
	N	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Possibility of the system falling from gravity.	During testing, we'll exclusively use a tripod. For the final product, we'll employ secure and non-destructive ceiling mounting to minimize instability and prevent falls.		
The system will be plugged into a wall outlet.	Caution will be taken when plugging or unplugging the system from the wall outlet. No sharp or hot objects should be left near any wires or components.		

References

[1] M. Eisoldt *et al.*, “A fully integrated system for hardware-accelerated TSDF SLAM with LiDAR sensors (HATSDF SLAM),” *Robotics and Autonomous Systems*, vol. 156, p. 104205, Oct. 2022, doi: https://doi.org/10.1016/j.robot.2022.104205.

HATSDF SLAM, an energy-efficient TSDF SLAM implementation for mobile robots, achieves real-time performance with 18 times lower energy requirements per frame than a state-of-the-art PC by leveraging embedded ARM processors and FPGA-based hardware accelerators. Its integrated ROS bridge enables online mapping inspection and offline evaluation of datasets, demonstrating accurate pose estimation with minimal drift in various scenarios compared to established SLAM algorithms. Future developments aim to implement runtime hardware reconfiguration for automatic adaptation to changing environmental conditions, enhance TSDF volume resolution, and reduce registration time for high-resolution LiDAR data using memory-efficient data structures and potentially incorporating feature-based SLAM methods.

[2] A. Geiger, P. Lenz, C. Stiller, and R. Urtasun, “Vision meets robotics: The KITTI dataset,” The International Journal of Robotics Research, vol. 32, no. 11, pp. 1231–1237, Aug. 2013, doi: https://doi.org/10.1177/0278364913491297.

The article introduces the KITTI dataset, a comprehensive resource for research in mobile robotics and autonomous driving, captured from a VW station wagon. Noteworthy aspects include 6 hours of diverse, calibrated, and synchronized traffic scenarios recorded with a range of sensors. The dataset provides 3D object labels and benchmarks, contributing significantly to the development and evaluation of computer vision and robotic algorithms for autonomous driving.

[3] T. T. Do and H. Ahn, “Visual-GPS combined ‘follow-me’ tracking for selfie drones.” *Advanced Robotics*, vol. 32, no. 19, pp. 1047-1060, 2018, doi: https://doi.org/10.1080/01691864.2018.1501278.

The paper proposes a hybrid approach for the 'follow-me' mode in camera drones, specifically selfie drones, aiming to improve targeting accuracy. Current commercial drones rely on GPS data for tracking, but this can lead to unsatisfactory results due to GPS inaccuracies. The proposed approach combines the short-term accuracy of a visual tracking algorithm with the long-term reliability of GPS-based tracking, demonstrating superior accuracy in follow-me operations compared to GPS-based methods. The system also exhibits quick recovery from visual tracking failures and Wi-Fi disruptions in short-term scenarios.

[4] E. Bostanci, B. Bostanci, N. Kanwal, and A. F. Clark, “Sensor fusion of camera, GPS and IMU using fuzzy adaptive multiple motion models,” Soft Computing, vol. 22, no. 8, pp. 2619–2632, Feb. 2017, doi: https://doi.org/10.1007/s00500-017-2516-8.

The paper addresses the challenges in user tracking for augmented reality (AR) applications, emphasizing the importance of accuracy and frame rate. It explores a fusion approach, combining vision-based estimates with GPS and IMU measurements to enhance tracking accuracy in outdoor environments. The use of Fuzzy Adaptive Multiple Models, a novel fuzzy rule-based approach, is investigated to improve accuracy and convergence speed in the fusion filter. The results demonstrate the developed tracking system's superior accuracy compared to conventional GPS–IMU fusion approaches, with applications highlighted in cultural heritage contexts.

[5] L. Veronese, F. AuatźCheein, T. Bastos, A. FerreiraźDeźSouza, and Edilson de Aguiar, “A Computational Geometry Approach for Localization and Tracking in GPS-denied Environments*,” Journal of Field Robotics, vol. 33, no. 7, pp. 946–966, Jul. 2015, doi: https://doi.org/10.1002/rob.21594.

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[6] A.-T. Popovici, C.-C. Dosoftei, and C. Budaciu, “Kinematics Calibration and Validation Approach Using Indoor Positioning System for an Omnidirectional Mobile Robot.” *Sensors*, vol. 22, no. 22, p. 8590, 2022, doi: 10.3390/s22228590.

The paper proposes an extended calibration approach to enhance the motion response of Omnidirectional Mobile Robots (OMRs) in indoor environments, specifically addressing mechanical imperfections such as misalignment. Utilizing an Indoor Positioning System (IPS) based on ultrasound technology, the study demonstrates significant reductions in motion errors, particularly in rotation correction factors. The research contributes to the advancement of precise and reliable navigation for autonomous mobile robots, crucial for applications in coordination and warehouse management.

[7] Zhu, Yu, and Xiao, “An Unconventional Multiple Low-Cost IMU and GPS-Integrated Kinematic Positioning and Navigation Method Based on Singer Model,” *Sensors*, vol. 19, no. 19, p. 4274, Oct. 2019, doi: https://doi.org/10.3390/s19194274.

The paper introduces an unconventional multiple low-cost Inertial Measurement Unit (IMU) and GPS-integrated kinematic positioning and navigation method based on the Singer acceleration model. The individual modeling method, a key component of this approach, dynamically adjusts systematic error estimations for each IMU in real-time, offering a more accurate representation of the actual situation. Despite the success of the proposed algorithm, the study highlights challenges related to the high computation load caused by frequent measurement updates in the Kalman filter, especially with IMUs operating at a high rate of 100 Hz. The paper concludes by suggesting future work on developing a more precise fusion algorithm using carrier phase information from the GPS.

[8] A. Saha, B. C. Dhara, S. Umer, K. Yurii, J. M. Alanazi, and A. A. AlZubi, “Efficient Obstacle Detection and Tracking Using RGB-D Sensor Data in Dynamic Environments for Robotic Applications,” *Sensors*, vol. 22, no. 17, p. 6537, Aug. 2022, doi: https://doi.org/10.3390/s22176537.

The paper proposes an efficient obstacle detection and tracking method using depth images, specifically with RGB-D camera sensors, for autonomous navigation in dynamic and cluttered environments. The approach employs a u-depth map for obstacle detection, with dynamic thresholding to enhance accuracy. Additionally, a restricted v-depth map technique is introduced for improved prediction of obstacle dimensions, and a novel algorithm facilitates obstacle tracking within the field of view. The system's performance is evaluated on various datasets, demonstrating its superiority over vision-based state-of-the-art methods in terms of state estimation of dynamic obstacles and execution time.

[9] Z. Liu, F. Zhang, and X. Hong, “Low-cost Retina-like Robotic Lidars Based on Incommensurable Scanning,” *IEEE/ASME Transactions on Mechatronics*, pp. 1–1, 2021, doi: https://doi.org/10.1109/tmech.2021.3058173.

The paper introduces a novel lidar sensor designed for mass production in autonomous robots, utilizing incommensurable scanning for straightforward manufacturing. Inspired by the human retina's fovea, the lidar exhibits a peaked central angular density, making it well-suited for applications requiring eye-like attention. Its unique design allows for higher resolution than conventional lidars, with demonstrated advantages in sensor calibration and potential upgradability, providing a promising solution for the development of cost-effective and efficient autonomous robots.

[10] T. Zhe, L. Huang, Q. Wu, J. Zhang, C. Pei, and L. Li, "Inter-Vehicle Distance Estimation Method Based on Monocular Vision Using 3D Detection." *IEEE Transactions on Vehicular Technology*, vol. 69, no. 5, pp. 4907-4919, 2020, doi: https://doi.org/10.1109/TVT.2020.2977623

The paper addresses challenges in autonomous vehicle perception systems, focusing on cost-effective solutions using monocular vision for inter-vehicle distance estimation. While traditional systems rely on expensive sensors, the proposed driving assistance system (DAS) leverages monocular vision-based methods. The study introduces a novel approach, combining 3D detection and an area-distance geometric model to enhance accuracy and robustness in inter-vehicle distance estimation. The method demonstrates superior performance in complex traffic scenarios, outperforming existing methods, with an accuracy deviation below 2% for vehicles with different visual angles.

[11] YoungWonks, "An introduction to magnetometers, where they are used and how they work," *YoungWonks*. https://www.youngwonks.com/blog/What-is-a-Magnetometer-and-How-Does-It-Work#:~:text=Based%20on%20the%20principle%20of

This article provides an overview of magnetometers, describing their function, working principles, applications, calibration methods, and types. It offers a detailed exploration of magnetometers, devices crucial for measuring magnetic fields' strength and orientation. It elucidates their devices working principles, including the Hall effect, magneto-induction, and magnetoresistance, each method discerning changes in current or resistance when exposed to magnetic fields.

[12] "What is Lidar? Learn How Lidar Works," *Velodyne Lidar*. https://velodynelidar.com/what-is-lidar/#:~:text=and%20weather%20conditions.-

The article introduces lidar (light detection and ranging), highlighting its use of eye-safe laser beams to generate a 3D representation of the environment. It explains the working principle of lidar: the sensor emits pulsed light waves, which bounce off objects and return to the sensor. By calculating the time taken for each pulse to return, the sensor determines the distance traveled, creating a real-time 3D map known as a point cloud. Overall, the article provides a clear and concise overview of lidar's functionality and applications.

[13] “How It Works: Xbox Kinect,” *Jameco.com*, 2019. https://www.jameco.com/jameco/workshop/howitworks/xboxkinect.html

This article delves into the inner workings of the Xbox Kinect, a revolutionary gaming device eliminating the need for a traditional controller and enabling full-body interaction within games. It describes the Kinect’s intricate software and hardware components. The software leverages extensive motion-capture data and utilizes artificial intelligence and machine learning algorithms to interpret real-life movements and map them onto virtual avatars. The hardware consists of an RGB color VGA video camera, a depth sensor, and a multi-array microphone, which collectively track various points on the player’s body. Overall, the article provides a comprehensive overview of the Xbox Kinects technology.

[14] “Apple AirTags: Everything You Need to Know” PCMag. https://www.pcmag.com/how-to/apple-airtag-tips

Apple AirTags are compact trackers designed to help users locate misplaced or stolen items using the Find My app. Priced at $29 each or $99 for a pack of four, AirTags use ultra-wideband technology and Apple's device network for precise location tracking. Setup is straightforward, requiring a compatible iPhone or iPad running iOS 14.5 or above. The device boasts a one-year battery life and uses standard CR2032 batteries. Security measures include end-to-end encryption, alerts for unwanted tracking, and NFC functionality for Android users to connect to lost AirTags. The product provides a blend of precision, security, and privacy for tracking personal belongings.

[15] “Starter Set Super-MP-3D” Marvelmind robotics. https://marvelmind.com/product/starter-set-super-mp-3d/

The Starter Set Super-MP-3D is a cutting-edge indoor positioning and navigation system designed for precise tracking in industrial settings. With ±2cm accuracy, it is ideal for automation, safety, and productivity applications. The versatile set supports multiple configurations, including 1D, 2D, and 3D, and offers Multi-Frequency support for increased update rates. Utilizing Super-Beacon technology with 6D IMU, the system provides superior performance compared to previous versions. It operates in license-free radio bands and includes advanced features such as ultrasound frequency selection and sharp DSP filters. The set is easy to deploy, with no manual calibration required, making it a comprehensive solution for indoor tracking of robots, vehicles, and drones.

[16] Teleoperator system with master controller device and multiple remote slave devices, by William T. Townsend. (2011, Aug 11.). US20120041599A1. [Online]. Available: https://patents.google.com/patent/US20120041599A1/en?oq=US20120041599A1

This patent describes using a master system to control multiple connected robots. The idea presented in this patent could be used as the GPS sensor developing could be the master system that streams data in cartesian space to its subordinate devices. We learned that multiple robots can be controlled from a master device rather than on-board hardware.

[17] Magnetic vector sensor positioning and communication system, by Larry W. Fullerton. (2016, Mar 24.). US9566599B2. [Online] Available: https://patents.google.com/patent/US9588599B2/en?oq=US9588599

This patent describes a magnetic vector positioning system that uses magnetic vector sensors to determine position or to transmit data. This has potential use of determining Romi orientation and position using magnetometers. We learned that magnetometers can also be used to transmit data and locate an object.

[18] Celestial navigation system for an autonomous robot, by Mark Joseph Chiappetta. (2005, Jul. 7). US7706917B1. [Online] Available: https://patents.google.com/patent/US7706917B1/en?oq=US7706917

This patent describes an onboard celestial navigation system for indoor robots. This could be used as a basis for mounting an external tracking system or an alternate way to obtain navigation data on board the Romis. We learned that a series of multiple beacons can be used for orientation and location data through relativity.

[19] Video image-based control system by Francis MacDougall. (1991, May 11.) US5534917A. [Online] Available: https://patents.google.com/patent/US5534917A/en?oq=US5534917

This patent describes a video-based tracking system where a video is converted to data to control a device. This can be used as a low-cost way to track multiple robots simultaneously. We learned that to process video, a computer performs and functions on a bitmap to determine whether an object is in an area of interest.

[20] Indoor robot positioning method integrating visual odometer and physical odometer, by 周唐恺. (2017, Jun 2.). CN107356252B. [Online] Available: https://patents.google.com/patent/CN107356252B/en?oq=CN107356252B

This patent illustrates a tracking method by way of using visual and on-board odometers to determine the location of a robot. This may be a more accurate way of tracking compared to solely digital tracking and it complements Romi's native odometer tracking. We learned that we could combine multiple existing solutions to improve location accuracy.

[21] Distributed localization systems and methods and self-localizing apparatus, by Marcus Hehn. (2016, Mar 7.). US20160259032A1. [Online] Available: https://patents.google.com/patent/US20160259032A1/en?oq=US20160259032A1

This patent describes using transceivers as a localization network that a device could use to determine its position relative to. This could be used as a solution where the robots would use the transceivers to compute its relative location on-board.

[22] Image-based georeferencing, by James M. Janky. (2009, Sep 14.). US20110064312A1. [Online] Available: https://patents.google.com/patent/US20110064312A1/en?oq=US20110064312A1

This patent describes an image-based system, which georeferenced features based on the difference between two pictures. This could be implemented by comparing a picture feed with Romi robots versus a reference picture with no robots.

[23] Triangular interferometric light-source tracker, by Brett Alan Bordyn. (1974, Jul 26.). US4003658. [Online] Available: https://patents.google.com/patent/US4003658A/en?oq=US4003658

This patent describes a system that tracks a light source using orthogonal triangular interferometric systems on a gimbaled platform. This can be used to track the position of a Romi by attaching a light source to the robot, though the mechanisms required are complex.

[24] Autonomous coverage robot navigation system, by Daniel N. Ozick (2008, Dec 23.). US8380350. [Online] Available: https://patents.google.com/patent/CN107356252B/en?oq=CN107356252B

This patent describes an autonomous robot that uses aa base station with three infrared emitters to guide the robot. This could be used by the Romi robots to determine their position based on their location from the emitter.

[25] Vision based location estimation system by . (2017, Jun 2.). CN107356252B. [Online] Available: https://patents.google.com/patent/CN107356252B/en?oq=CN107356252B

This patent describes using multiple Kalman filters to process data from an ultra-wideband positioning system, pressure sensors, temperature sensors, and inertial measurement data, to obtain precise location data. This process could be used to combine several onboard sensors already implemented on the Romi with the prototype to further increase the precision of positional data.