Conceptual Design Review

Perception System Using Stereo Vision and Radar

Team A

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Sponsored by: Delphi Automotive

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1. Project overview

1.1 Background information

Current self-driving cars such as those used by Google and Uber have a number of limitations, especially in their perception systems. These perception systems are bulky, expensive, and hard to maintain, due to the large number of redundant sensors used for perception as can be seen in figures 1 and 2. On the other hand, shown in figure 3 is the self-driving car designed by our sponsors, Delphi Automotive.

Figure 1. Google Self-Driving Car

Figure 2. Uber Self Driving Car

Figure 3. Delphi Autonomous Driving Vehicle

The car in figure 3 is one of the first self-driving cars to make a cross country drive across the United States. As can be seen from the above image, this autonomous vehicle has its sensors integrated into the vehicle body, which makes for a sleek design.

What we aim to do in this project is to combine the input from multiple sensors into a standalone sensor system that can be fit to a car and enable perception for autonomous driving purposes. Our perception system will use fewer sensors compared to current driverless cars, and will therefore be cheaper and easier to install and maintain. Additionally, our sensors will allow for a low-profile perception system like the one integrated into the car pictured above.

1.2 Project Description

Stereo vision and radar are two sensor systems that are commonly used for short-range and long-range perception, respectively. In this project, we aim to combine these two sensor systems to develop a stand-alone perception system for use in autonomous vehicles. By doing so, we plan on creating a system that can simultaneously perceive in both the long and short range. Using this, we aim to create a reliable virtual environment around the vehicle that the user can use to gain information about his/her driving surroundings. Eventually such a system would allow for cheaper, more accessible, and more robust self-driving cars.

2. Use case

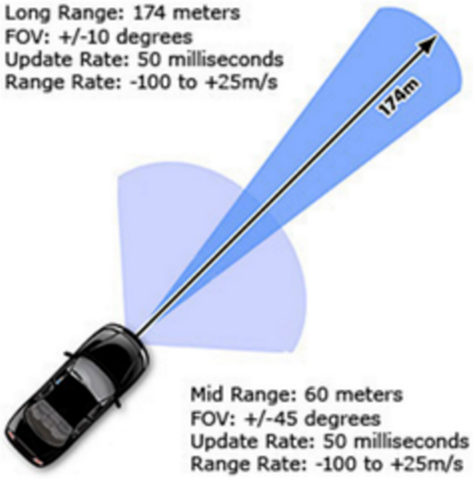

Figure 4. Radar Range Representation

Driverless Car Corp. recently lost one of their autonomous cars. Despite this driverless car being equipped with multiple redundant camera and LIDAR systems, it crashed into a white truck that reflected sunlight into the car's perception system. Driverless Car Corp. stock fell sharply, and the CEO of the company, Mr. Dusk, was faced with scrapping its extensive sensor array system project and starting from scratch. Moreover, recent consumer reports had shown Mr. Dusk that a major complaint about their autonomous cars was the bulkiness and difficulty of maintaining the sensor array system. Users were also not happy with the appearance of these cars. What is Mr. Dusk to do?

Enter the EagleSense3000 from Team Aware! As can be seen from the image above, our perception system simultaneously perceives long and short range objects, at a sweep rate of 20 Hz. Moreover, it combines both radar and stereo vision technology, so that even in bright sunlight or pitch darkness, our radar system can be used to detect virtually all possible obstacles (such as big white trucks). Of course, under favorable conditions, the stereo vision system provides for a very robust means of analyzing our environment in 3D. Since the perception system is based on three individual sensors – two cameras for stereo vision, and one radar unit – the system does not cost as much as systems like Mr. Dusk's. Additionally, the system is designed to be standalone – it does not depend on a car's make or model or on any other perception or actuation systems that a car might have. This feature, plus the small form factor of our sensors, make for sleek and adaptable perception system that could be used by any manufacturer of autonomous vehicles.

Now that he has scrapped his latest perception sensor array, Mr. Dusk proceeds to try out the EagleSense3000 from Team Aware. He picks up the sensor rack and easily places it on top of a car with autonomous capabilities (that had its old sensor array removed). The sensor system is lightweight, low-profile, and easy to setup – within a couple of minutes Mr. Dusk has already secured the sensor rack to the top of the car and connected the computer system to the car's display and actuation systems. Amazed at the ease of installation, Mr. Dusk eagerly enters the car to see the system perform!

As the car drives around the city, the EagleSense3000 astutely and reliably displays a virtual environment on the car's infotainment screen, while sending outputs to the cars many actuators that enable it to drive. It starts to rain, but the weatherproof, hydrophobic, oleophobic housing of the sensors makes the rain a non-issue. Later, the sun comes out and shines of a lot of puddles in the road into the cameras. Once again, this is not an issue for the EagleSense3000 as the radar sensors use radio waves. Just as the car makes its way back to our testing facility, a crazy pedestrian dashes across the road in front of the car. Thankfully, due to the fast sensor sweep and the dual modes of perception, the pedestrian is detected, and the brakes are applied perfectly. Mr. Dusk is completely impressed.

In the end, the perception system proved to be superior to the ones used by Driverless Car Corp. in nearly every way. Mr. Dusk was able to make vast improvements to the autonomous vehicles produced by his company, while simultaneously reducing costs, all thanks to a well-designed, improved perception system – the brain of the driverless car!

3. System-level requirements

The system-level requirements are categorized as Mandatory (M) or Desirable (D), as well as Performance (P) and Non-functional (N).

3.1 Performance requirements

Table 1. Performance requirement details

ID	Title	Description
M.P1	Conduct full-range perception	The system shall detect the object up to 150 m
M.P2	Perceive in real-time	The system shall acquire sensor data from the camera and radar at up to 20 Hz
M.P3	Use multiple sensors	The system shall fuse and unify the data from radar and stereo camera up to 50 m
M.P4	Detect and identify objects	The system shall detect object size with an accuracy of up to 80%
M.P5	Classify objects	The system shall classify objects with an accuracy of up to 70%
M.P6	Estimate vehicle motion	The system shall estimate vehicle motion with an accuracy of up to 90%
M.P7	Detect object velocity	The system shall detect object velocity with an accuracy of up to 80%
M.P8	Detect object distance	The system shall detect object distance with an accuracy of up to 95%

3.2 Non-functional requirements

Table 2. Non-functional requirement details

ID	Title	Description
M.N1	Works in real-time	The system will work in real-time
D.N1	Weather-proof	The system will be robust in all weather conditions (including rain, fog, snow, etc.)
D.N2	Functions in all lighting conditions	The system will work properly in all kinds of lighting environments (including strong sun light, daylight, night, etc.)
D.N3	Concealable within the vehicle	The system will be concealable totally in the car body
D.N4	Compatible with vehicle display systems	The system will be able to be integrated into the already existing vehicle display systems

4. Functional Architecture

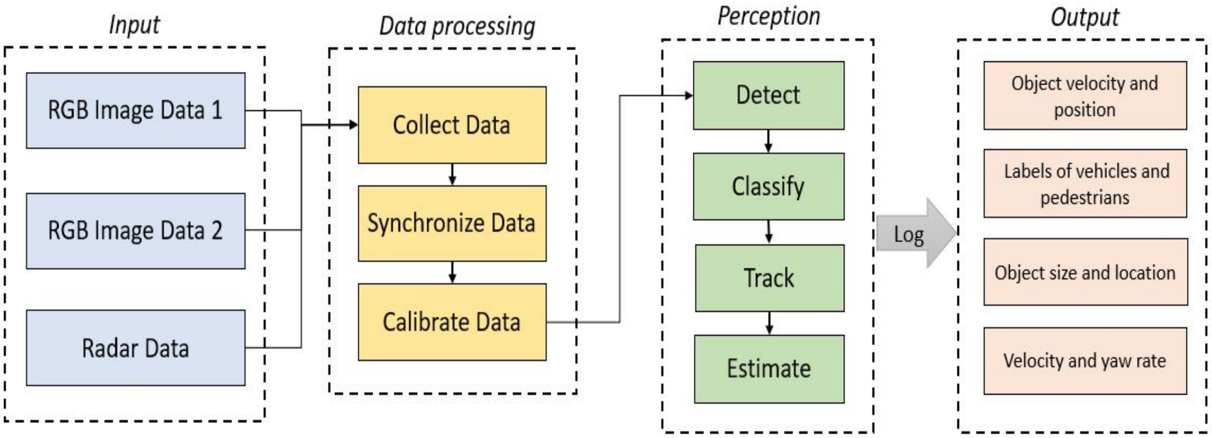

Figure 5. Functional Architecture of the system

A diagram illustrating the functional architecture of our system is shown in figure 5. The whole process that transforms inputs from sensors to outputs is mainly composed of two steps, namely data processing and perception.

Note that even though only two types of sensors, namely camera and radar, will be used, there will be three different sets of data as inputs to the system, two from the two cameras and one from the radar. This is because of the stereo vision system being constructed using two identical single-lens global shutter image sensors instead of directly adapting an existing stereo vision camera in the market, as the baselines of existing ones are all too short to cover the desired range for autonomous driving applications.

4.1 Data Processing

First of all, incoming data from all different sources should be collected together and stored in the system. More importantly, the time axes of different sets of data need to be aligned and synchronized with each other, since specific applications of the system have suggested fairly high demands on real-time data and its reliability.

While the proposed stereo vision system might only have the ability to provide short-range detection within 60 meters, the radar can cover up to 175 meters for both short-range and long-range detections. Therefore, short-range detection information would be available from both sensors. This overlap of data offers an advantage in performing calibration tasks, to compare individual dataset with each other in order to ensure a relatively high reliability of the data before forwarding it to the perception module.

4.2 Perception

In the perception module, tasks can be roughly divided into four categories, namely the object detection, classification, tracking, and motion estimation. With fused data coming into the module, these tasks will be executed in a sequential order as demonstrated in figure 5 above. The order is determined based on the dependencies of each task.

The first task is to detect objects in the scene formed by the fused data. Secondly, the detected objects will be classified into groups and be further identified. The system should be able to distinguish between vehicles and pedestrians by extracting features from image data. Within the group of vehicles, the type of a vehicle should also be recognized. Labels of these classified objects should be displayed in the output of our perception system.

Furthermore, detected objects from the first task should also be identified as either static or moving. Specifically, the system should be able to track the moving objects in order to investigate their positions and velocities over time. For static objects, their size and location information are desired instead. Again, the desired information from both static and moving objects should be available in the output of the system.

Last but not least, the 3D motion of the perception system, expressed in terms of velocity and yaw rate of the cameras, can be estimated based on results from previous tasks such as object detection and tracking. Since the perception system will be rigidly mounted on the testing self-driving vehicle, the 3D motion of the vehicle can therefore be estimated, too.

In summary, raw input data from sensors will be processed first and fused to create a virtual environment of the perceived scene in real world. In this virtual environment, objects should be detected and classified with labels. Their kinematic and spatial information, along with ego-motion of the vehicle, should be also provided. This augmented reality environment containing all the information above will be the final output of the perception system. It can be directly interpreted by onboard computer to help generate commands to control the vehicle, or displayed to driver and passengers onboard through the vehicle infotainment display system.

5. System-level trade studies

The project's success largely depends on choosing the appropriate sensors for the application. A stereo vision system, and another complementary system that can perceive depth and objects independent of vision, is desired. The reason for this is to avoid a scenario where some of the sensors are not perceiving the environment accurately. By combining stereo vision with another means of sensing depth, the aim is to calibrate the sensors with one another (so that a given object is detected as being at the same distance away by both systems thus verifying the data).

5.1 Cameras

To conduct stereo vision, the team had to choose between global shutter cameras, rolling shutter cameras, and RGB-D cameras. To make an informed decision, the team conducted the following trade study as shown in table 3.

Table 3. Camera trade study details

Attribute	Importance	Global shutter	Rolling shutter	RGB-D
Cost	4	2	5	3
Performance at high speed	5	5	2	3
Ease of use	3	4	3	2
Stereo performance	5	5	3	1
Field of view	4	3	2	5
Noise rejection	5	4	2	1
Total		102	72	63

Global shutter cameras are expensive, but they allow capturing the scene instantly, while avoiding warping and edge distortions that would occur in a rolling shutter camera at high speeds as can be seen in figure 6. RGB-D cameras may allow for a wider field of view, but are limited by their range of depth sensing. Additionally, stereo RGB-D is hard to implement due to IR interference between the two camera systems. In the end, after careful analysis using the trade study, the team chose to go with two identical global shutter cameras for constructing the stereo vision sensor.

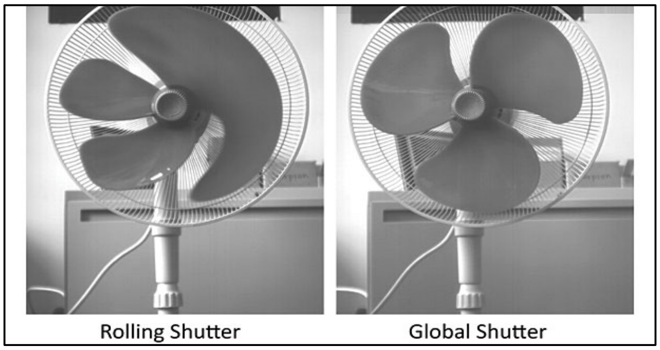

Figure 6. Rolling shutter vs global shutter

5.2 Lenses

When choosing lenses for the camera, desired the working distance of 60-80m (for stereo vision) had to be factored in, as well as the desired field of view (approx. 80 degrees). Given a sensor size of 1/1.8”, an 8mm focal length lens was chosen, based on a few assumptions. Assuming our working distance is ~70m and our field of view is ~130m (so ~90° FOV), a focal length of ~7.6mm would be needed, since the sensor size is 1/1.8" = 14.11mm (using the Gaussian lens formula). Alternatively, if the desired field of view is set to 130m and the desired focal length to 8mm, a working distance of 73.7m is achieved, which is in the desired range of 60-80m.

5.3 Long range depth sensor

To sense depth independently of stereo vision, the was an option to choose between radar, lidar, and sonar sensor systems. Lidar has been recently used in virtually every autonomous vehicle; however, it was found that it has some limitations compared to radar which are well explained by the trade study conducted as shown in table 4.

Table 4. Depth sensor trade study details

Attribute	Importance	Radar	Sonar	Lidar
Cost	5	3	5	2
Light sensitivity	5	5	5	3
Dust/fog sensitivity	5	4	3	2
Ease of maintenance	4	5	4	3
Rate of sensing	4	3	1	5
Field of view	4	2	3	5
Size of sensor	3	4	4	3
Ease of use	3	4	2	3
Range	5	4	1	5
Total		144	120	130

Lidars are more expensive and harder to maintain due to the moving parts. Additionally, they are usually larger in size for the same performance specification. Sonar is a lot slower than both radar and lidar, and hence would not be a wise choice for an autonomous vehicle. Radar can function effectively in various lighting conditions, it has no moving parts, and it has a small form factor. On the downside, however, it has a narrower field of view and slightly shorter range compared to lidar. In the end, a radar system in conjunction with our stereo vision system was chosen to best fulfill the needs of the project based on the trade study conducted.

6. Cyber-physical Architecture

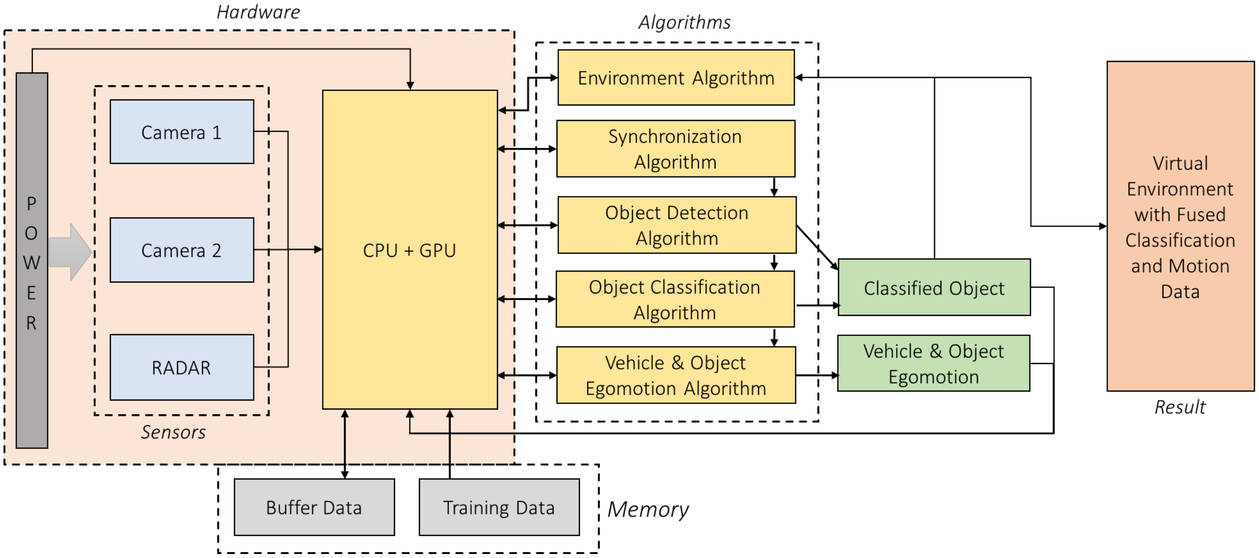

Figure 7. Cyber-physical Architecture of the system

The Cyber-physical architecture of project’s intended solution is presented above in figure 7.

There are two major subsections in the cyber-physical architecture, namely the hardware and the software. Due to the focus of the project on building a perception system, all arrows except the ones outwards from power, represent information flow. The arrows outwards from power represent the flow of energy.

6.1 Hardware

The hardware section, represented on the left, contains the power source, the sensors and the processing unit. The power source supplies energy in the form of electricity to the sensors and the processing unit. There would be different power sources used under different stages of the project. For example, a regular AC power socket of 120 Volts might be used for indoor testing of the sensors in the earlier stage, while a DC cigarette lighter receptacle of 12 Volts might be used for later system testing onboard the vehicle.

The sensors used for building the system include an electronically scanning radar and a stereo vision system composed of two identical cameras. These sensing units altogether should be able to collect information/data about the vehicle’s surrounding environment in real time. All raw data should be simultaneously passed to the processing unit, where all data synchronization and calibration tasks, as well as all software programs for perception tasks, will be implemented at the same time. The processing unit essentially serves as the center of all communications among our standalone perception system.

6.2 Software

The software section, represented on the right of the cyber-physical architecture, contains the algorithms, the memory, the data flowing in and out through software programs based on the algorithms, and the final result. The central processing unit, most likely with the assistance of a separate graphics processing unit, processes the incoming data using the appropriate algorithms. These algorithms in turn yield subsets of data required to the final algorithm, which processes them to form the virtual environment along with all desired information of objects inside the environment.

More detailed information and specifications regarding each major hardware and software component mentioned above in the system, namely the power source, the sensors, the processing unit, and the four perception algorithms, are further illustrated in the Subsystem Description sections.

7. Subsystem Description

7.1 Mounting Rack

The self-designed mounting rack serves as the physical structure to accommodate all components of the perception system on the testing vehicle. The structure will be most likely made of 80/20 Aluminum. Both the stereo vision subsystem and the Radar should be attached rigidly on the mounting rack so that their relative position is also fixed. The mounting rack should be attached on the testing vehicle in a way such that it does not require any large-scale or complicated modification on original components of the vehicle. It should also protect the sensors from being damaged by severe weather or road conditions such as rain, snow, dirt, or gravels. Most importantly, the mounting location shall offer a completely unblocked view of the environment to be detected around the vehicle.

7.2 Power Source

The power source takes in an AC input at 120 Volts and 60 Hz. For the initial stages of the project, this will be taken from a standard wall socket. Eventually, when the solution is implemented in a vehicle, then alternatives will be considered like using a DC input or a portable AC power source. The AC power is converted to required DC voltages for the sensors using an off-the-market AC to DC power converter.

7.3 Sensors and Sensing Subsystem

The sensors are a set of 3 hardware components which further sub-components. There are two identical cameras that will be used to build a stereo camera subsystem. The model of the camera is the Grasshopper3 3.2 MP USB3 Vision by PointGrey Research. The camera is used in tandem with a lens to get the intended field of view. The model of the lens is Tamron 8mm 1/1.8” C mount lens by PointGrey Research. Each of the cameras require 5V DC power input, which will be provided by the power source. These cameras will be aligned and fixed relatively to each other in order to render a stereo vision of the environment, as well as depth information of objects in the environment. The other sensor used is an electronically scanning radar sensor. The model of the

Radar sensor is the ESR 2.5 developed by Delphi. The data collected by these sensors is transmitted to the processing unit.

7.4 Processing Unit

The processing unit consists of the Central Processing Unit (CPU) and the Graphics Processing Unit (GPU). A GPU will be used in order to provide results in real time by harnessing the parallel computing abilities of a multi-core GPU. The processing unit is connected to the memory unit for information/data storage. The memory unit contains two main forms of memory, the buffer data and the learning data. The buffer data stores the data from the previous frames of data which could be useful in applying algorithms to the current frame's data. The learning data contains the data model which will be utilized by algorithms which employ learning based methods like deep neural networks. There is a two-way flow of information between the processing unit and the buffer data, and a one-way flow from the learning data to the processing unit.

7.5 Perception Subsystem and Perception Algorithms

There are multiple algorithms which will be employed for the functions required to achieve success for this project. There are five algorithms which will be utilized sequentially to attain the intended final result. The particular algorithms haven't been identified yet and the team is using placeholder names for the algorithms which describe the function of the algorithm which will be eventually used.

7.5.1 Synchronization Algorithm

The first algorithm is a synchronization algorithm. This takes in the data provided by the two cameras and the radar sensor. After processing, the time instant when the two cameras click an image is coordinated and this data is further matched with the data from the radar sensor so that an accurate instantaneous representation of the environment can be created. The accuracy and precision of this algorithm is essential to the success of the perception system in meeting the intended requirements.

7.5.2 Object Detection Algorithm

The second algorithm is an object detection algorithm. This takes in the data from the sensors, synchronized by the synchronization algorithm. This algorithm aims to detect feature points in the environment and eventually detect objects like pedestrians, other vehicles and stationary objects. One of the methods the team is looking at is using segmentation techniques in a learning based environment to accurately detect objects. Once the algorithm is executed, the intended output is a list of objects with their segmentation bounds to use for further algorithms.

7.5.3 Object Classification Algorithm

The third algorithm is an object classification algorithm. This takes in the list of objects detected by the object detection algorithm. This algorithm aims to identify/classify the object into pre-defined categories such as pedestrians, SUV, truck, sedan and other categories for natively stationary objects. The possible methods that will be utilized for this will almost certainly be based on deep learning and will involve a lot of training data. The accuracy of this algorithm will help in creating category specific movement models for the objects which is a major part of the intended solution.

7.5.4 Object Motion Estimation Algorithm

The fourth algorithm is an object motion estimation algorithm. This takes in the categorized list of objects in multiple frames of images along with the learnt motion models for the categories. Using this data, the algorithm will estimate the direction and motion characteristics including, but not limited to, roll, pitch, yaw, acceleration, velocity and position of every object in the current frame including the vehicle on which the sensors are mounted. These motion characteristics for the vehicle on which the sensors are mounted is collectively called the ego-motion. This algorithm is essential for the perception system to be used for autonomous driving applications. After the execution of this algorithm, a list of objects will be made with each object's category, position on the road/environment, motion and direction characteristics available including the ego-motion of the primary vehicle. Furthermore, the ego-motion can be compared with data from an onboard Inertial Measurement Unit (IMU) for calibration purpose.

7.5.5 Environment Creation Algorithm

The final algorithm is an environment creation algorithm. This algorithm uses the results from the classification and estimation algorithms to map the objects on a unified environment which fuses the inputs of the stereo vision cameras and the radar with label and graphics depicting the characteristics of each of the objects. This algorithm is not only essential for the information that will be used for autonomous driving applications, but also to visually display the environment is which the vehicle is. This will also be used to visually validate the working of the system and to showcase the system to the world in an easily understandable manner. The final result of this algorithm will be a virtual environment with fused classification and motion data.

8. Project Management

8.1 Work Plan and Tasks

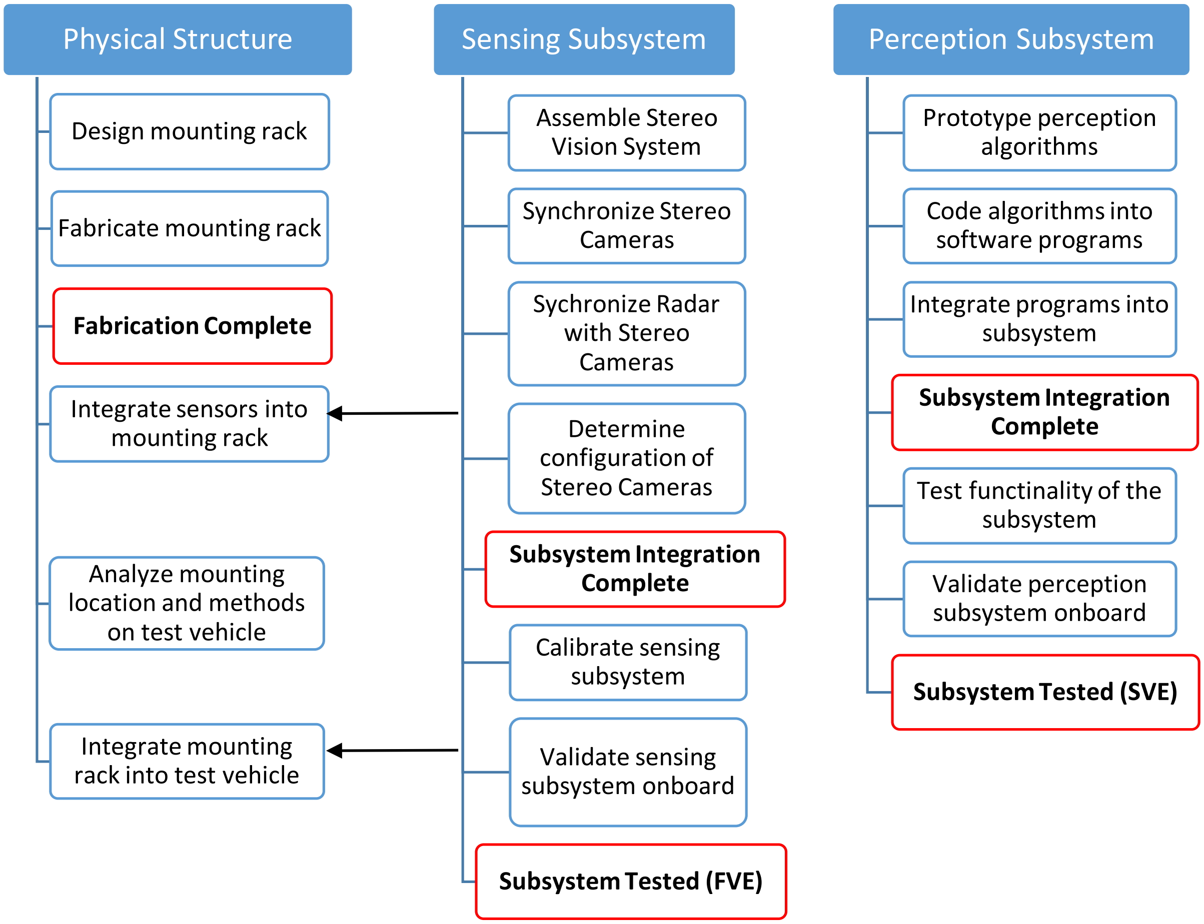

Figure 8. Work plan and task details

The diagram in figure 8 above shows the team's proposed work plan. The entire project of developing the standalone perception system can be divided into three components, namely to develop the physical structure, the sensing subsystem, and the perception system. All technical tasks that are necessary to complete each component and to successfully achieve the project goal are listed in the diagram. For certain tasks, the black arrows are used to indicate their dependency on other tasks.

In addition, the bold items boxed in red are major milestones that have been identified for the project. Since the diagram is organized in chronological order from top to bottom, all blue-boxed items above a certain milestone are tasks that need to be accomplished in order to reach the milestone.

8.2 Schedule and key milestones

Table 5. Milestones and Schedule details

No.	Milestones	Date	Dependency
	Fall Semester		
1	Mounting rack fabrication complete	10/21/16	N/A
	Preliminary Design Review (PDR)	11/01/16	N/A
2	Sensing subsystem integration complete	11/21/16	1
3	Sensing subsystem tested onboard	12/05/16	1 and 2
	Critical Design Review (CDR)	12/12/16	N/A
	Spring Semester		
4	Perception subsystem integration complete	03/27/17	N/A
5	Perception subsystem tested	04/17/17	4
6	Whole system tested onboard	05/01/17	3 and 5

Table 5 above demonstrates all milestones of the project in a desirable timeline through the two-semester timespan. During the Fall semester, the team proposed to completely finish designing and fabricating the mounting rack and get approximately 40 percent of the sensor synchronization done before the Preliminary Design Review (PDR) on November 1st, 2016. Experiments on configuration of the stereo cameras can be performed once the mounting rack is ready to use, and radar can be synchronized and calibrated with the stereo cameras at the same time. A complete sensing subsystem fixed on the mounting rack should be tested altogether on the testing vehicle before the Critical Design Review (CDR) by the end of the semester.

In the Spring semester, the team planned to spend most of the efforts on developing the perception subsystem. A fully functional perception subsystem after tuning and debugging should be available by April 17th, 2017. The whole system should be tested on the testing vehicle at least two weeks before the delivery to sponsor.

A more detailed schedule including major tasks and their durations is displayed in the Gantt Chart on the next page in figure 9.

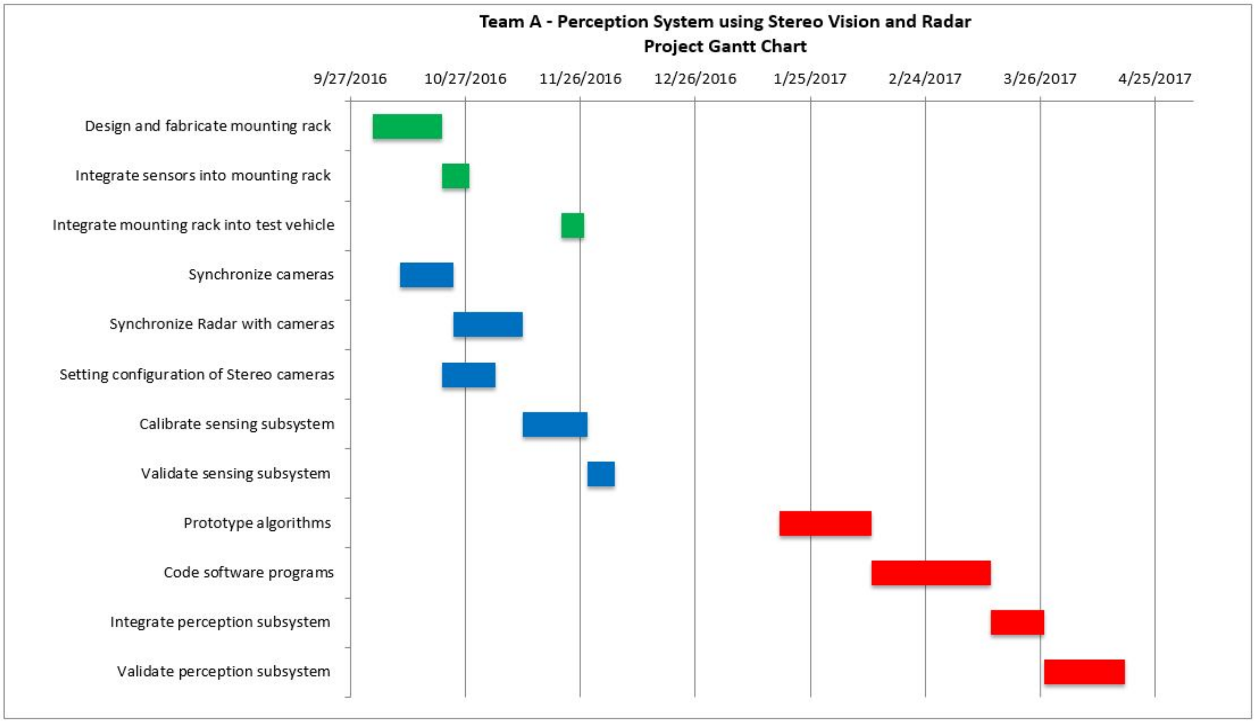

Figure 9. Gantt Chart

8.3 System validation experiments

There are multiple system validation experiments to be performed in both, Fall and Spring semesters.

8.3.1 Fall semester

For the Fall semester, the plan is to finish the hardware part of the system, synchronize the data from stereo camera and radar, then get the data from the sensors. The test conditions including the location, the equipment and the environment required are shown in table 6. The complete steps and performance requirements of the FVE for hardware validation are shown in table 7. The complete steps and performance requirements of the FVE for sensor synchronization are shown in table 8.

Table 6. Fall testing conditions

Location	Roads around school
Equipment	Car ,mounting rack, cameras, radar
Environment	Sunny day with fine slight

Table 7. Hardware Validation steps

Steps	Fix the rack on the car and measure the relative position of the sensors
	Drive around the school for about 20 minutes
	Measure the relative position of the radar and camera again
Performance	The sensors should be fixed and there should be no changes in the relative position in any conditions including, but not limited to sudden braking, bad weather, rash driving.

Table 8. Sensor Synchronization steps

Steps	Fix the sensors on the mounting rack and put them on the car
	Drive around the school for about 15 minutes
	Monitor the data collected by the stereo camera and radar and make the comparison of data's timeline
Performance	Data from stereo camera and radar should be synchronized and show in real-time (less than 100ms delay)

8.3.2 Spring Semester

For this semester all the software parts which includes detecting, classifying the object and estimating the ego motion of the vehicles will be completed. The test conditions including the location, the equipment and the environment required are shown in table 9. The complete steps and performance requirements of the SVE for Object Detection are shown in table 10. The complete steps and performance requirements of the SVE for Object Classification and Estimation are shown in table 11.

Table 9. Spring testing conditions

Location	Roads around school
Equipment	Car, mounting rack, cameras, radar, GPU/CPU
Environment	More than 15m wide road with more than 30/min traffic flow in any conditions

Table 10. Object Detection steps

Steps	Fix the sensors on the car and drive with 20mph around the school
	Get the synchronized data from cameras and radar
	Detect the objects on the road and return the size, color, shape information
Performance	Detect object size with an accuracy of 80%, distance with an accuracy of 95%, velocity with an accuracy of 80%

Table 11. Object Classification and Estimation steps

Steps	Following the above steps of object detection
	Use the data collected before and give the classification of the pedestrians and vehicles with labels on them
	Estimate the ego motion and give the information of velocity, position and orientation of the car
Performance	Classify objects with an accuracy of 70% and estimate vehicle motion with an accuracy of 90%

8.4 Team Member Responsibilities

Team A is composed of five members with a wide range of abilities. Team Member Responsibilities are depicted as shown below in table 12.

Table 12. Team Member Responsibilities

Team member	Area of Expertise	Primary responsibilities	Second responsibilities
Amit Agarwal	Mechanical & Computer Science	Hardware set up& Synchronize data	Calibrate data
Harry Golash	Mechanical & Computer Science	Hardware & Calibrate data	Object detection
Yihao Qian	Computer Vision & SLAM	Object detection, classification & tracking	Object estimation
Menghan Zhang	Controls & Electronics	Object classification, tracking & estimation	Synchronize data
Zihao Zhang	Mechanical & Signal Processing	Object detection & classification	Sensor fusion

8.5 Parts List and Budget

Provisional parts list and budget is shown below in table 13.

Table 13. Parts list and budget details

No.	Description	Cost	Quantity	Sponsored	Total
1	Grasshopper3 3.2 MP Color USB3 Vision (GS3-U3-32S4C-C)	$975	2	√	0
2	Delphi ESR 2.5 24V Radar	$3300	1	√	0
3	Tamron M118FM08, 8mm, 1/1.8", C mount Lens	$210	2	√	0
4	12V, 18W, Power Supply with Hirose HR25 Circular Connector (one per camera unit)	$65	2	√	0
5	Fresco FL1100, 4 Port, USB 3.0 Host Controller Card (only one for both units	$60	1	√	0
6	USB 3.0, 3m, Type-A to Micro-B (Locking) Cable (one per camera unit)	$10	2	√	0
7	GPU/CPU	TBD			0
8	Computer	TBD			0
9	Mounting Rack	TBD			0

8.6 Risk Management

A key aspect to completing a successful project is to have good risk management strategies. This involves anticipating possible worst-case scenarios in advance and planning accordingly. By doing so, we can preemptively design solutions or back up plans should we ever encounter these scenarios. We approached risk management in three categories:

8.6.1 Technical difficulties:

Table 14. Risk management for technical difficulties

	Possible problem	Solution
1	PCB for power supply breaks	Have multiple power supply PCBs
2	Stereo cameras won't synchronize	Use an extral pulse to signal the cameras
3	A sensor is faulty or does not work	Contact sponsor for a replacement ASAP
4	Car power supply not sufficient for sensors	Buy a battery pack or amplifier
5	Computational resources not sufficient	Use a GPU for faster processing

8.6.2 Personnel difficulties

Table 15. Risk management for personnel difficulties

	Possible problem	**Solution**
1	Team is inexperienced in computer vision	Consult with an outside expert or delegate some tasks
2	Team member falls ill for a long period of time	All other team members share the tasks
3	Disagreement among team members	Open rational conversation and use compassion
4	Sponsor is not responsive	Actively pursue sponsors and provide regular updates
5	Miscommunication among the team members	Make sure team members clarify before making decisions

8.6.3 Scheduling difficulties:

Table 16. Risk management for personnel difficulties

	Possible problem	**Solution**
1	Sensors and components do not arrive on time	Research readily available components within budget
2	Project milestone unlikely to be met	See if team can put in more hours or move deadlines
3	Part breaks and is out of stock before the demo	Try to borrow a replacement from CMU or sponsor
4	Sensor rack fabrication taking too long	Work in parallel on synchronizing sensors

9. References

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