“As simple as possible, but no simpler”¹: a vision-based approach to the DARPA Urban Challenge

Lead Organization: Princeton University

Sarnoff Corporation as a substantial subaward

Technical Contacts
Princeton University
Engineering Quadrangle
Princeton University
Princeton, NJ 08544

Technical Contacts Continued...
Princeton University
Engineering Quadrangle
Princeton University
Princeton, NJ 08544

Department of Operations Research & Financial Engineering
Fax: 609-258-4363
Prof. Alain Kornhauser, Team Leader
609-258-4657, alaink@princeton.edu
Prof. Patrick Cheridito, Co-PI
609-258-8281, dito@princeton.edu
Prof. Alexandre d’Aspremont, Co-PI
609-258-8773, aspremon@princeton.edu
Prof. Robert J Vanderbei, Co-PI
609-258-2345, rvdb@princeton.edu

Department of Computer Science
Fax: 609-258-1771
Prof. Thomas A. Funkhouser, Co-PI
609-258-1748, funk@cs.princeton.edu
Prof. Szymon M Rusinkiewicz, Co-PI
609-258-7479, smr@Princeton.EDU
Prof. Robert Schapire, Co-PI
609-258-7726, schapire@cs.princeton.EDU

Department of Electrical Engineering
Fax: 609-258-3745
Prof. Bradley Dickinson, Co-PI
609-258-4644, bradley@princeton.edu
Prof. Sanjeev Kulkarni, Co-PI
609-258-6727, kulkarni@princeton.edu

Technical Contacts
Sarnoff Corporation (subaward)
CN5300
Princeton, NJ 08543-5300
Manaj Aggarwal,
609-734-2320, maggarwal@sarnoff.com
Harpreet Sawhney,
609-734-2320, hsawhney@sarnoff.com

Administrative Point of Contact:

Michelle D. Christy, Director
Office of Research & Project Administration
Princeton University
Princeton, NJ 08544
Tel: 609-258-3090, FAX: 609-258-1159, awards@princeton.edu

¹ Albert Einstein
Executive Summary

Princeton University’s approach to the Urban Challenge is to build upon our successes in the 2005 GC by designing a reliable and robust vision-based system with advanced navigation capabilities. We will divide this task into the creation of three subsystems: WorldView, Command, and Control. The WorldView module defines how we represent the world as data. WorldView is composed of GlobalView and LocalView. GlobalView relies on GPS/Inertial data to represent where the vehicle is located in the network defined by the RNDF. LocalView represents obstacles sensed by the Vision algorithms in a reference frame fixed to our vehicle, such that each object is assigned a probabilistic position and velocity. Command is responsible for continually generating desired speed and heading values. To achieve this, Command examines both LocalView and GlobalView data to radiate "feasibility cylinders" through space-time. These cylinders are ranked in order of safety and relevance to the mission goals; at each instant in time, the highest-ranked cylinder determines the desired velocity vector for the vehicle. An expert system stochastically determines if the vehicle should enter a specific maneuver state. Velocity vector decisions made by Command are implemented by the Control module. The control loops and actuators that will be used in our vehicle will be similar to the technologies that we successfully implemented in our 2005 GC entry. Rigorous testing will be done both in simulation and at a physical testing ground.

Our design philosophy strives for simplicity and generality wherever possible, and is expected to result in a reliable and robust vehicle. In the Command system, rather than focusing on a highly modularized approach with scripted behaviors, we propose a more general system that will be able to react to unexpected or dangerous situations without having direct knowledge of those scenarios pre-programmed in. WorldView will be kept simple by using machine vision as the primary sensory system. A vision-based navigation system is capable of performing all of the sensory tasks needed for driving in an urban environment. By limiting the number of sensors used, we also limit the potential sources of error. Vision is furthermore a passive sensing technique, eliminating concerns about interference and location broadcasting. Sarnoff Co., our key subcontractor, will be responsible for providing us with a reliable vision system. In doing so, they will draw upon their 25 years of experience in developing and testing machine vision solutions. Sarnoff’s current capabilities, which include algorithms for lane and road-edge detection, obstacle tracking, and visual odometry, will be extended to directly address our needs for the Urban Challenge. Our team will also tap into the vast intellectual resources of Princeton University. Nearly a dozen professors across four departments will be undertaking research initiatives to develop and extend our systems during the course of the Urban Challenge. Object recognition, scene reconstruction, Command maneuver selection and adaptive Control will all benefit from their efforts to understand and account for the uncertainties associated with urban driving.

With the exception of Sarnoff’s vision contributions, the project will be carried out by Princeton University students and faculty, including many of the key personnel from the 2005 Challenge. Work teams for WorldView, Command, Control, Systems Integration, Testing, and Reliability Optimization will be formed. Each team will be jointly led by a professor and a student. Professor Alain Kornhauser will reprise his role from the previous Challenge as Team Leader.
Table of Contents

1 Technical Approach..................................................................................................................... 6
  1.1 WorldView............................................................................................................................ 6
    1.1.1 Two-tiered hierarchy to WorldView: GlobalView (Gv) and LocalView (Lv)................... 6
    1.1.2 Object identification and attribute estimation................................................................. 7
      1.1.2.1 Field Of View Coverage.......................................................................................... 8
      1.1.2.2 Visual Odometry....................................................................................................... 9
      1.1.2.3 Road surface, Lane and Road-edge detection......................................................... 9
      1.1.2.4 Obstacle Detection, Classification and Tracking................................................... 10
      1.1.2.5 Object Classification.............................................................................................. 10
  1.2 Command............................................................................................................................... 11
    1.2.1 Collision-avoidance/Lane-keeping .............................................................................. 11
    1.2.2 Navigation..................................................................................................................... 12
  1.3 Control .................................................................................................................................. 12
  1.4 System Integration ................................................................................................................ 12
    1.4.1 Adaptive Control and Integration.................................................................................. 13
  1.5 Testing................................................................................................................................... 13
    1.5.1 Development of a simulation environment.................................................................... 13
    1.5.2 Physical Testing Plan..................................................................................................... 13
  1.6 Novel Approaches to Computer Vision............................................................................... 14
    1.6.1 Bio-inspired algorithms for robust vision-based control............................................ 14
    1.6.2 Application of Sparse Principle Component Analysis (PCA) to Image Classification 14
    1.6.3 Reliability Estimates..................................................................................................... 14
  1.7 Existing systems and platforms ............................................................................................ 14

2 Team Description....................................................................................................................... 15
  2.1 Major Sub-contractor.......................................................................................................... 16
    2.1.1 Automotive safety......................................................................................................... 16
    2.1.2 Robotic Vision, Navigation, and System Integration.................................................... 17
  2.2 Background of Key Individuals on the Princeton/Sarnoff Team ......................................... 18
  2.3 Involvement of Princeton University Personnel................................................................. 20
    2.3.1 Funding source for Princeton University participants.................................................. 22
  2.4 Roles and Involvement of Sarnoff Personnel....................................................................... 22
  2.5 Forrestal Campus Test Facility ............................................................................................ 22
    2.5.1 Physical Testing............................................................................................................ 23

3 Management and Funding Plan ................................................................................................. 24
  3.1 Personnel Plan..................................................................................................................... 24
  3.2 Task Breakdown & Milestone Schedule .............................................................................. 24
    3.2.1 Vision Tasks.................................................................................................................. 24
  3.3 Costs.................................................................................................................................... 27
  3.4 Funding Plan......................................................................................................................... 30
  3.5 Export Laws and Regulations .............................................................................................. 30
  3.6 Attachments A, B, C, & E.................................................................................................... 30
Abbreviations:

**Ca:** Collision Avoidance  
**DARPA:** Defense Advanced Research Projects Agency  
**GC:** Grand Challenge  
**FOV:** Field of View  
**GPS:** Global Positioning System  
**Gv:** GlobalView  
**GUI:** Graphical User Interface  
**IMU:** Inertial Measurement Unit  
**LIDAR:** Light Detection and Ranging  
**Lk:** Lane-Keeping  
**Lv:** Local View  
**MDF:** Mission Data File  
**OD:** Obstacle Detection  
**PII:** Prospect Eleven, Princeton's entrant into the 2005 GC  
**PerceptOR:** Perception for Off-Road Robotics  
**Prospect Ten:** Princeton’s entrant into the Urban Challenge  
**PTZ:** Pan-Tilt-Zoom  
**PU:** Princeton University  
**RADAR:** Radio Detection and Ranging  
**RAID:** Redundant Array of Independent Disks  
**RNDF:** Route Network Definition File  
**UC:** Urban Challenge  
**UGV:** Unmanned Ground Vehicle  
**Wv:** WorldView

References

1 Technical Approach

Princeton University's goal in the upcoming DARPA Urban Challenge is to develop a reliable and robust solution to the challenge of autonomous travel through an urban environment. We learned from our experience in the 2005 GC that simplicity often leads to reliability. In a simple system with fewer components, there are fewer opportunities for errors. Also, focusing on a limited number of modules allows for a fuller exploration of the capabilities and limitations of each system, increasing the reliability of each module. A simple design also makes discovering and fixing errors more straightforward. We propose to break the challenge into three key components: WorldView (sensory input and perception), Command (cognition), and Control (actuation).

WorldView (Wv) focuses on creating a coherent and concise data representation of the urban road environment as constructed from the flow of information from an array of sensors and the given RNDF. These data of the surrounding environment will be used by the Command system to make informed driving decisions on both local and global scales. Prospect Ten’s primary sensory system will be based on machine vision. We have selected vision for three reasons. First, vision is a passive sensing technique. Active options like LIDAR and RADAR may interfere with other vehicles, or reveal the vehicle's location when stealth is required. Secondly, the urban driving environment is designed around humans who rely on vision, and thus all information embedded in the roadways can be seen using vision, such as lane boundaries and (though not for the challenge) road signs. Thirdly, vision processing can be used to extract other information about the vehicle's surroundings beyond obstacle and lane detection, including visual odometry and obstacle classification. This reduces the need for or greatly simplifies the burden of other sensors. Supporting vision will be low resolution proximity sensors in the “blind spots.” Nominally precise GPS and inertial motion sensors will be combined with the RNDF to provide data for high level navigation.

Prospect Ten’s command system will consist of two tiers. At the higher level, a path between waypoints will be generated using the RNDF to enable appropriate decisions at intersections. Then a stochastic expert system will combine global and local data to produce an appropriate maneuver to execute, such as a lane change or K-turn. The lower level will make the lane keeping and obstacle avoidance decisions. The algorithm that was used in the 2005 challenge will be extended naturally to handle objects moving at constant velocities.

Existing control loops and actuators used in the 2005 GC will implement the desired heading and speed received from the Command module. Each system is linearized using inverse nonlinearities or nonlinear feedback, and then a controller is synthesized using classical methods. Custom-built actuators manipulate vehicle controls while allowing full human drivability at the flip of a switch. Reliability will be achieved through probabilistic filtering, and maintaining explicit uncertainty estimates. Innovative research that is expected to yield significant additional reliability and robustness will also be undertaken.

1.1 WorldView

WorldView focuses on creating a concise data representation of the urban road environment as constructed from the flow of information from an array of sensors and the given RNDF.

1.1.1 Two-tiered hierarchy to WorldView: GlobalView (Gv) and LocalView (Lv)

WorldView will be characterized into a two-tiered hierarchy: GlobalView and LocalView. GlobalView focuses on the large-scale road network including road closures to be used in
Navigation. LocalView is responsible for tracking all objects and local features within a 150m radius, especially dynamic ones such as moving vehicles for Lane keeping and Collision avoidance.

By correlating nominal GPS and inertial data with that of the RNDF, Gv will be capable of providing the vehicle with a sense of place in its broader mission and urban environment through a 2D model of the world that includes such specific features as:

- Intersections where stopping, turning, merging and diverging can occur.
- Multiple Lanes / Dotted Lines where vehicles can pass or be overtaken.
- Roundabouts where specific rules-of-the-road apply.
- Parking lots where restrictions on travel lanes is relaxed.
- Speed limit
- Valid roads / travel paths

Given this sense of place, Prospect Ten will know what constraints and opportunities it has to navigate through the urban environment to best achieve its mission.

LocalView focuses on the details associated with the broader mission. It will be built primarily from vision sensors. It is assumed to begin as an endless, featureless plane relative to the nose of the vehicle. It is the responsibility of the image system to place objects in that featureless plane and to assign appropriate attributes to each of the object. We intend to use three binary object classifications as follows:

- Fixed / not fixed to the world coordinate system
- Within / outside feasible lane of travel
- Necessary / not necessary to avoid

Thus, trees and other road furniture are fixed, usually outside the lane of travel and don’t need to be avoided if they are outside the lane of travel and the vehicle is inside the travel lane. Lane markings are fixed, inside (or at the boundary) of the feasible area and may or may not be necessary to avoid. A stop line, for example, is to be avoided until it is safe for the vehicle to proceed. This classification is expected to significantly simplify the creation and application of the object’s data structure. This will allow us to focus different resources on different objects as appropriate. For example; if an object is fixed, then estimation of relative velocity is expected to be simplified. Similarly if an object is identified to be a tree, it can be expected to be located outside the feasible lanes of travel.

### 1.1.2 Object identification and attribute estimation

Using a combination of stereo image processing, edge detection and feature segmentation integrated from multiple cameras, it will be possible to identify, classify, size and assign instantaneous location and velocity attributes to individual objects (solid body combinations). In addition, because of the inherent noise and unreliability of any sensor system, explicit current reliability estimates will be assigned to each attribute. These reliability estimates will enable us to perform explicit tradeoffs between risk and reward and address the Command and Control aspects in a stochastic and non-deterministic context. We believe that this will substantially improve the inherent robustness of the vehicle’s autonomous operation.

This critical portion of the project will be conducted by the Sarnoff Corporation in cooperation with faculty and students from Princeton University. Sarnoff has over 25 years of experience with real-time computer vision and image processing, in particular in robot perception and automotive safety. Sarnoff has developed and field-tested algorithms and software for obstacle detection, vehicle following, object tracking, terrain mapping, lane
departure warning, and imminent collision sensing. These techniques have been demonstrated on moving vehicles, in cluttered environments, and in uncontrolled weather and lighting conditions. In addition to algorithms and software, Sarnoff has real-time vision processing expertise using PCs and the Acadia® I Vision Accelerator board; the Acadia® performs complex front-end vision processing (e.g., depth estimation from stereo) so that the PC may perform additional vision processing tasks.

1.1.2.1 Field Of View Coverage

Figure 1 shows the area around the vehicle that needs to be monitored for driving in urban traffic (not all regions need to be monitored all the time). The vehicle is represented by the blue rectangle in the center of the figure, and the colored triangles represent the Field Of View of different stereo cameras, indicated below (the FOV and range requirements are based on Sarnoff’s past experience with autonomous robotic and automotive applications):

- The green area in front of the vehicle is covered by three stereo pairs with 45 degrees FOV each, providing sufficient resolution for detecting obstacles up to 30m. This configuration has been tested in the Sarnoff’s PerceptOR program.
- The orange areas are needed to check for approaching traffic at an intersection and before passing a stopped or slower vehicle. Each corresponds to a stereo camera with 15 degrees FOV, providing detection up to 120m.
- The blue areas (side and rear of the vehicle) are used when checking for approaching traffic before a lane change maneuver. They have similar FOV to the forward looking short range cameras (green) and provide detection up to 30m.
- Depending on the final placement of the rear-looking cameras, one more stereo pair may be needed to monitor the area right behind the vehicle (light orange in the figure) for the cases when the vehicle is moving in reverse. A shorter detection range (e.g. 15m) is sufficient for this camera.

A selective attention scheme will be developed based on the premise that the areas around the vehicle need to be monitored at varying frequencies depending on the current operating mode (road or vehicle following, traversing an intersection, etc.). Below we describe the major vision components that will be provided by Sarnoff.

Figure 1: Field Of View coverage for operation in an urban environment
1.1.2.2 Visual Odometry

Sarnoff’s Visual Odometry (also known as Vision Aided Navigation) system estimates the 3D motion of the host vehicle by a) performing robust detection and tracking of image features over multiple frames to establish point correspondences over time, and b) estimating 3D camera attitude and position from these correspondences by employing algebraic 3D motion constraints between multiple frames to rapidly generate and test numerous pose hypotheses. Sarnoff has further demonstrated that the real-world performance of vision-aided navigation can be substantially improved by employing multiple cameras in a generic distributed aperture configuration and the use of GPS and INU data (when available). An illustration is shown in Figure 2. This sequence starts outdoors (where GPS is available) and continues indoors (where GPS is not available) and passes through clutter and regions of poor lighting and sparse features. Despite this, the system shows excellent performance. For the scenarios expected in the UC, the proposed system shall reset the Visual Odometry reference frame at reliably detected waypoints to reduce (local) trajectory drift.

1.1.2.3 Road surface, Lane and Road-edge detection

Sarnoff has developed modules for road surface, lane and road-edge detection. Given a stereo pair of images, a set of features is extracted from the left and right images to obtain 3D points. This point cloud is analyzed to determine which points lie on the road surface, and of those surface points, which are likely to be lane markers or road edges. Once the road and lane boundary points are located, a geometric model is fitted to describe the shape of the road around the host vehicle. From this model, one can estimate the proximity of the host to the lane or road boundaries, and also the bearing of the host vehicle with respect to its lane. This information can be used for both lane-keeping and lane departure (passing, turning) control. Sample results for the lane detection module are illustrated in Figure 3 (left and right lanes are indicated on the road in green and red, respectively).

For the current effort, we propose two enhancements to the existing module:

- We propose to use ego-motion data from the host vehicle such as speed and yaw-rate to aid the fitting of the road shape model, for increased robustness
- For unmarked (and unpaved) roads, we propose to use an approach that estimates the location of the vanishing point contour from texture orientations on the unpaved road surface and tracks it over time to establish road curvature and pitch.
1.1.2.4 Obstacle Detection, Classification and Tracking

Sarnoff has developed vision-based techniques for obstacle detection, imminent collision detection, and detection and tracking of vehicles from moving vehicles.

The single-frame obstacle detection function analyzes stereo-derived depth (range), groups the 3D structure into discrete objects, and associates a threat level with each object. For the current effort, Sarnoff will further improve this algorithm by investigating the use of multi-resolution processing. It will also group detected obstacle regions into a single obstacle based on local connectivity. This detection algorithm also uses information from the road awareness algorithm to compensate for the pitching motion of the host vehicle, and to direct the search for potential detections in the correct locations around the host vehicle.

A number of target confirmation algorithms, based upon 3D features, image content and temporal consistency, are used to verify potential detections.

Sarnoff has also developed techniques for predicting collisions between the host vehicle and stationary or moving obstacles by estimating the trajectories of detected obstacles and finding the intersection between these trajectories and that of the host vehicle. Figure 4 shows an example of imminent collision detection: the red box indicates an obstacle, and the yellow bulls-eye shows the predicted impact location (a missing bulls-eye would indicate that there will be no collision). For improved performance (low false positive rate), obstacles will be tracked and their lateral and longitudinal velocities estimated as accurately as possible.

1.1.2.5 Object Classification

The use of monocular object classification allows the effective range of the vehicle's stereo vision-based obstacle detection system to be increased substantially. Although this is a difficult problem for general objects, the distinctive nature of certain objects encountered in an urban environment, primarily vehicles, makes this domain significantly better-suited for image recognition.

At Princeton, researchers Thomas Funkhouser and Szymon Rusinkiewicz have developed a “shape search engine,” publicly accessible at http://shape.cs.princeton.edu/, that incorporates research into matching 3D shapes to each other and to 2D images. The main research results have been novel “shape descriptors,” compact representations of 3D shapes that are easily indexed, rapidly searched, invariant to different classes of transformations (most crucially rotation and translation), and that provide guaranteed bounds on shape similarity.

We intend to research algorithms for finding vehicles and intersections by building upon recent work for scene recognition that begins with image descriptors characterizing the local distribution of colors and edges within patches in the image. A statistical generative model is then used to infer the probability that each patch is due to a particular class of objects (e.g., trees, ground, sky, buildings), and the distribution of object classes is used to characterize the type of scene.
Extending this “graphical modeling” approach to object recognition entails computing the probability that each patch belongs to a particular kind of object; the probabilities are themselves influenced by the distribution of objects within the entire image. This approach potentially has many advantages over traditional methods that segment the scene and compare image patches directly to a database of examples. For example, the methods may be less sensitive to the variation of lighting within the scene, and may be more tolerant of occlusion. Additionally, the system ensures that each element within the scene is consistent globally; for example, that cars are not floating above the road plane.

1.2 Command

The Command system is responsible for making real-time decisions at two levels: Navigation and Collision-avoidance/Lane-keeping (Ca/Lk), based on the representation of the urban environment assembled by WorldView. Navigation encompasses network-level decisions, such as: continue forward on the road ahead, take 3rd exit at roundabout, turn around, shift lanes, stop at stop line, yield, etc. These are real-time decisions associated with opportunities and constraint in the road system to best achieve the overall mission as defined by the RNDF. Collision-avoidance/Lane-keeping focuses primarily on selecting a proper speed and heading of the vehicle at every instant of time to best achieve the current Navigation decision. In addition there are some less critical decisions such as toggling the turn signals and shifting into reverse that are part of the Command process.

Conceptually, P11’s basic Command architecture was structured as follows. P11’s WorldView was an ensemble of its identified obstacles and GPS lane boundaries. From these data it computed the best unobstructed gap ahead by radiating forward for each feasible heading a “feasibility rectangle” from the nose of the vehicle that was slightly wider than the vehicle itself. Each rectangle was extended up to a convex intersection with an obstacle or a GPS boundary or until it reached a specified maximum length. Discrete jumps in the lengths of these rectangles defined feasible gaps in the road ahead. A rating mechanism chose the best of the feasible gaps. The vehicle’s instantaneous steering angle aimed the vehicle to the center of the best gap and the speed was simply set to be proportional to the length of the instantaneous rectangle that passed through the center of that gap. By sequentially “shooting gaps” between obstacles and lane boundaries, P11 autonomously navigated through an RNDF. For the Urban Challenge, both are substantially more difficult. Navigation must chose among a list of maneuver opportunities, the simplest of which is move down the road ahead and Ca/Lk must contend with moving objects all around the vehicle, not just stationary objects and lane boundaries in the road ahead.

1.2.1 Collision-avoidance/Lane-keeping

Because at least some objects in WorldView other than Prospect Ten may be non-stationary, P11’s rectangle extrusion and gap shooting methodology will need to be extended to a 3rd dimension; time. Infeasible regions occupied by the various obstacles and delineated by lane boundaries will be mapped. Extruded through this space will be families of feasibility rectangles that conform to the vehicle’s available Navigation decisions over the next several seconds. The simplest of these families will be those associated with a range of steering commands at constant and slightly changing velocities. In other situations more complex extrusions that represent more complex maneuver for the next several seconds will need to be made. The extent to which each rectangle can be feasibly extruded will be a measure of the quality of the decisions associated
with that extrusion. Instantaneous desired speed and heading will be set to the best of these feasibility rectangles.

Initially, we will assume that each object in $W_v$ travels at a constant velocity. We will investigate the need for acceleration estimates. We will also investigate the use of expanded infeasibility as a possible efficient way to address the uncertainty of an object’s future speed. Finally, we will investigate the assignment to each extrusion a risk metric that is proportional to the proximity to objects having large uncertainties in size, position and/or velocity.

1.2.2 Navigation

The command segment needs to have a more extended global WorldView than just moving “forward” in the direction of the RNDF. It must have a navigation component as well. That is, if the road splits, it will need to choose the best fork. It needs to have the option of backing up or turning around and trying something else. In an open area where no objects or boundaries are to be avoided it needs a higher order goal. Thus an arc-node network map will be constructed from the RNDF. Map-matching using GPS data will locate the vehicle on the map. Standard shortest path computations will be used to specify the branch decision. The focus of the task will be to investigate and develop a coding methodology that analytically characterizes as many of the rules as possible.

Additionally, we will need to decide on the maneuver state of the vehicle with explicit consideration for the uncertainties of the urban environment. We propose to investigate the types and effects of uncertainties encountered in an urban environment, and develop a stochastic expert system that will demonstrate safe, effective, ground-vehicle navigation in urban traffic. The expert system will control complex behaviors that include navigating from waypoint to waypoint, re-planning routes, interpreting lane markings, commanding context-dependent speed control, following other vehicles safely, pulling around stopped vehicles, traveling through intersections, stopping safely at designated points, making sharp, “K”, and “U” turns, backing out of a cul-de-sac, merging and de-merging into traffic, parallel parking, and avoiding obstacles and neighboring traffic.

1.3 Control

Control encompasses the implementation of the command decisions. As such, it involves its own set of actuators, independent sensors and feedback loops that provide a robust implementation of the desired controls. Prospect Ten will use P11’s control systems for steering, brake (nominal and emergency), throttle and gear change. Each has been upgraded and made more responsive and reliable. We also expect to receive a second vehicle from a major automobile manufacturer. This vehicle will have electronic steering, braking and gear changing in addition to the electronic throttle control that was originally part of Prospect Eleven. We will need to add an emergency braking system and a steering angle sensor, both of which we will clone from P11. Everything else including such things as actuation of turn signals we should be able to address electronically in Systems Integration.

1.4 System Integration

Each of these separate systems need to be brought together and operate as a whole. Each system will have its own primary computing platform. Excess computing resources will be shared through a task management system that can dynamically rebalance the workload across our set of networked processors in the event of a malfunction. Such a system allows continued operation even when processors have been fully disabled.
For ease of coding, versioning, and debugging, we have selected to use Microsoft’s C# language on the Windows Server 2003 platform. The Visual Studio package allows rapid development and deployment of a GUI for monitoring the software developed for Vision, WorldView, Control, and Command, as well as the computing performance of our system.

1.4.1 Adaptive Control and Integration

Any intelligent system requires the interaction of sensory information, perception, and cognition (reasoning, planning, categorization, etc.) which typically results in control of some motor effectors. The flow and negotiation of information in systems of such complex and heterogeneous functions requires sophisticated control, appropriate communication interfaces, and overall system integration. The use of learning and adaptive strategies becomes critical when system design complexity surpasses the designer's ability to specify in detail the flow of information and necessary communication interfaces within the system. We will investigate these issues of system integration for the application under study.

1.5 Testing

1.5.1 Development of a simulation environment

We will develop simulation software that will be primarily used to test the performance of the Command system. In this environment, vision will be assumed to be perfect within the specified field of view of the vehicle’s cameras. This will allow us to focus on rigorous testing of the Command module. Simulated GPS coordinates will allow us to test dynamic route planning with RNDF and MDF files, while simulated roads, intersections, lanes, parking lots and obstacles will allow us to examine the local Command decisions made under all scenarios encountered in the Urban Challenge.

Sarnoff currently has a testing platform for its vision systems that will be used to test the range and reliability of each camera system.

1.5.2 Physical Testing Plan

Individual systems will be tested as they are implemented (i.e. actuators, proximity sensors, etc.). Once the Command module and vision system have been thoroughly tested as described above, the vehicle will be brought to Princeton’s Forrestal Campus for full system testing. Initially, specific maneuvers such as k-turns, lane changes and simple obstacle avoidance will be tested. When these maneuvers can be executed reliably, larger test courses will be set up that incorporate route planning and lane following.

1.6 Novel Approaches to Computer Vision

Arguably the biggest challenge of autonomous operation is effectively dealing with uncertainty. Consequently, the major intellectual element of this challenge and its greatest long-term contribution is expected to be research into the uncertainties associated with autonomous driving. In this section we propose some specific basic research initiatives that are expected to substantially improve the robustness of Prospect Ten. Even without these we are confident that our technical approach can address all of the elements of the urban challenge; however, with the following initiatives, we expect to assemble a truly remarkable vehicle.

1.6.1 Bio-inspired algorithms for robust vision-based control

The problem of robust navigation in the presence of large uncertainties and unpredictable environments has in a sense already been mastered by flying insects. Insects integrate
information from a wide variety of sensory inputs, including visual and mechanical sensors, with incredibly fast response times, and in order to gain insight into how to design engineered navigation systems with robust behavior in uncertain environments, one may turn to inspiration from these naturally evolved systems.

Visual systems of insects respond to movement of the image pattern on the retina, called optic flow, and it is believed that a relatively small number of sensory outputs are formed from these optic flow fields and used for obstacle detection and flight control [4]. The essential idea is to use spatially integrated properties of the optic flow field as a small number of “sensors” to use for feedback for flight control. Recent work has explored similar strategies for control of Unmanned Aerial Vehicles (UAVs), and several crucial capabilities have already been demonstrated on land vehicles using this approach, including obstacle avoidance, and driving down a tunnel or between buildings [5]. The central question to be addressed in this research thrust is how to extract the most relevant information from the optic flow field, so that more complex tasks can be achieved.

Techniques for constructing such relevant basis functions can be borrowed from the study of control of fluid flows, in which techniques such as Principal Component Analysis are used to extract coherent structures from fluid flow fields [7]. Similarly, these techniques may be used to identify obstacles, which appear as coherent structures in the optic flow field. It is likely that traveling structures and self-similar structures will also be important in optic flows, and methods for extracting these structures have been recently developed [8–9]. Techniques from control theory can also be used to identify the most significant outputs for a given system, for instance by examining observability Gramians of a system linearized about a particular state (for instance, driving straight or turning).

1.6.2 Application of Sparse Principle Component Analysis (PCA) to Image Classification

PCA is an algorithm which effectively decomposes an image into primary features. It often forms the basis of object recognition systems. One of the key shortcomings of PCA is that it produces dense factors, i.e. the weights in the linear combination are typically all non-zero. By trading off some explanatory power we can increase sparsity and gain substantial computational efficiency through use of semi-definite relaxation procedures. [10-11]. Such approaches have shown promise in separation of facial features, and reducing sensitivity to occlusions. We will investigate their application in object identification.

1.6.3 Reliability Estimates

As time elapses it is critically important to track individual objects and assemble a history of attribute values. Time series analysis techniques will be used to generate current reliability estimates for each of these attributes. We will extend the simple notions of repeated observations used in P11 with more formal estimation of confidence intervals from historic data. Since conditions should be assumed to be continuously changing, we will use several neural-network type learning approaches to continuously “tune” the reliability estimates based on recent performance under changing conditions.

1.7 Existing systems and platforms

Participation in the 2005 GC allows Princeton University to begin the ‘07 Urban Challenge with a proven autonomous platform. P11 is a modified GMC Canyon fitted with drive-by-wire actuators, power management electronics, networked processors, and data acquisition equipment. It is equipped with a failsafe emergency brake system to ensure safe
operation and testing. Prospect Eleven has logged numerous autonomous miles, especially after
the 2005 GC when it traversed all of the navigable portions of the 2004 and 2005 GC courses.
Included were autonomous traverses of both Beer Bottle Pass and Daggett Pass at night when
only P11’s headlights provided sufficient illumination for its stereo-vision object detection
system.

P11’s drive-by-wire modifications are relatively stable technologies. P11 has never been
disabled by actuator failure. The vehicle’s throttle is controlled electronically. The brake pedal is
mechanically controlled by a custom-built linear ball-screw actuator used for autonomous
operation, and a pneumatic piston for emergency braking. These are connected to the brake pedal
with steel cable, such that a human operator can override the brakes, even during autonomous
operation. A potentiometer monitors the position of the actuator. Steering control is
accomplished via direct gear connection with the steering column. An optical encoder provides
precise rotary position feedback. Prospect Eleven also has the ability to shift the transmission,
although the necessary actuators were disabled during the GC competition.

A deep-cycle battery bank and a 1500 Watt inverter/charger unit provide a steady power
supply to onboard electronics. The system charges from the stock alternator during engine
operation. The vehicle’s computing resources consist of networked processors rack-mounted on
fluidic shocks designed to attenuate high frequency noise. Each processor contains its own
memory and multiple hard drives in a redundant RAID array for reliability. These precautions,
designed for the former off-road environment, should be more than adequate in an urban
environment. A LabJack digital acquisition unit and a RoboteQ motor controller interface the
vehicle’s controls to the computing system. These units allow control of indicator lights and
actuators, and monitor individual wheel odometry data, transmission position, brake lights, and
engine conditions. Finally, P11 has in place a low level software interface that handles device
communication, inter-process communication, and feedback control of actuators. The software
framework is a multithreaded, event-based architecture designed to allow the most current
sensory data to be used immediately.

P11’s high level sensor processing and decision making software was sufficient for the
2005 GC, but will require the substantial extensions described above to address the Urban
Challenge. Current sensor processing capabilities include stereo obstacle detection, and
probabilistic sensor fusion. P11’s existing stereo detection algorithms combined with temporal
filtering can detect car-sized obstacles at a range of only 15m.

Finally, software tools designed for the previous challenge will ease development for the
urban challenge. Much of P11’s decision making software was designed and tested in a 2D
simulator prior to implementation on the vehicle. The simulator’s capabilities include low speed
vehicle dynamics, multiple vehicle simulations, dynamic obstacle placement, and GUI displays.
The simulator implements realistic uncertainty in sensor measurements, so that filtering
techniques can be tested. The GUI displays both ground truth and filtered position estimates to
allow analysis of uncertainty and its influence on decision-making. Simulator performance has
been found to track real vehicle performance well.

2 Team Description

The Princeton Urban Challenge team is fortunate to have as its nucleus most of the key
student and faculty composition of the 2005 GC team. Strengthening this experience is the
addition of Sarnoff Corporation’s 25 years of experience in real-time computer vision and image
processing, in particular in robot perception and automotive safety. Substantial participation by
additional faculty and students expert in learning, classification, reliability, risk analysis and robustness will further bolster the team.

As was the case with the 2005 GC, the Princeton team is an academic team composed of faculty, researchers and students. This team is responsible for all phases of the project. Organization follows closely and improves upon the group organization that was used effectively in the 2005 GC. The groups are organized into subject areas. They are each led and directed by a faculty member that is a world-class expert in the field. Implementation responsibility rests on the creative talents of the undergraduate members of the group as was done with the 2005 GC; however, additional innovation will be brought to bear throughout this effort by the active inclusion of advanced graduate students and post-docs, especially in the Reliability Group where true innovation is expected. It is firmly held that participation in this challenge provides the faculty, post-docs and graduate students with an excellent testing ground for their basic research. This is why they are enthusiastic to participate in and contribute to the Urban Challenge.

The Princeton team is organized into six (6) groups as follows and as presented in Figure 2.1:

- **WorldView Group**: Overseeing the Sarnoff Corporation responsibility for Vision and contributing to fundamentally improving image enhancement
- **Command Group**: responsible for developing testing and integrating the decision systems
- **Control Group**: responsible for implementing the Command decisions. They are responsible for all of the hardware elements of the system.
- **System Integration Group**: responsible for assembling all of the subsystems, developing and maintaining the computing hardware and ensuring “thread-safe” operation.
- **Testing Group**: responsible for designing and building the simulation software system, preparing the physical test site at the Forrestal Campus of Princeton University and developing the appropriate test schedule and systems that will properly test both the individual subsystems and the overall integrated system.
- **Reliability Group**: responsible for basic research investigations into Learning, Classification and Risk Analysis that are expected to substantially improve the reliability and robustness of autonomous operation in a real and uncertain urban environment.

Each of these groups will be led by a member of the Princeton University faculty and assisted by a student who played a key role in Princeton’s participation in the 2005 GC.

### 2.1 Major Sub-contractor

Sarnoff Corporation is the major subcontractor to the team. Sarnoff has over 25 years of experience with real-time computer vision and image processing, particularly in robot perception and automotive safety. Sarnoff is primarily responsible for delivering a “bolt-on” vision system and all of the software components that provide current estimates of the attributes of each object in the vehicle’s field of view. They will also assist in the formal system integration and test program.

They bring the following relevant experience and examples of related current activities:

#### 2.1.1 Automotive safety

**NIST/ATP Collision Avoidance**

Under the NIST ATP program on Advance Vision-Radar Threat detection, Sarnoff Corporation is working with Ford and Autoliv, a Tier 1 automotive supplier, to advance the state of the art in vision-based collision detection algorithms and further, to fuse vision and radar sensors using powerful processing algorithms that will identify and evaluate impending collisions in time to
take advance action. As per the proposal, AVRT is designed to perform hazard detection and collision mitigating triggering within 50 ms, allowing mitigation of 50-mph collisions. Its false-alarm rate will be less than one per billion miles driven, enabling its widespread acceptance by the public and it will be verified in a technology transferable to an ASIC, enabling broad deployment as a low cost consumer product. At the time of this writing, the program has passed the first performance review and is in its second year of development.

2.1.2 Robotic Vision, Navigation, and System Integration

PerceptOR
Prime Contractor: Carnegie Mellon University
POC: Lynn Young
Tel Nr. 412-268-1206
Subcontract Nr. 116221-1130013
Period of Performance: March 16, 2001 - March 31, 2004
Prime Contract Nr. MDA972-01-9-0016

Under the DARPA PerceptOR program, Sarnoff has developed and implemented real-time algorithms for stereo-based obstacle detection and mapping. These modules have been integrated on the Blitz team UGV and demonstrated in different off-road environments during the PerceptOR filed tests. The obstacle detection function analyzes stereo derived range data to associate a traversal cost with the 3D structure discovered by the stereo process. These are accumulated over time using vehicle pose information to produce an obstacle map that is used in path planning through some form of cost minimization. The obstacle detector analyzes data in local map coordinates rather than range-image pixel coordinates and uses multi-resolution to detect obstacles characterized by different slopes; it corrects for the ground aspect ratio of pixels in a UGV range image and includes a slope contribution, which could be reported separately. The algorithm produces an analog output that measures obstacle severity so that subsequent thresholding can determine which obstacles are considered to be lethal. The mapping module takes as input instantaneous 3D and cost data and projects this into a world-centered data structure that represents an extended region of terrain around the vehicle using a grid of map cells.

U.S. Army Physical Security and Equipment Monitoring MDARS-E program
Prime Contractor: General Dynamics Robotic Systems
Sarnoff contributed stereo-based obstacle detection (OD) and mapping functionality. By running on the MDARS-E robot, the OD system was successfully proven to function with a platform that included a pan-tilt head for fast, wide area terrain scanning. The stereo ranging was accurate enough to permit correct positioning (without blurring) of obstacle data in a cost map in the presence of rapid pan-tilt head motions. The stereo OD algorithm is also compatible with camera rotations, and provided stable obstacle assessment as the stereo head underwent pan and tilt maneuvers. In addition to the OD system, Sarnoff also provided scene stabilization and moving target indication (MTI) and tracking capabilities to the MDARS-E intruder detection system. Both the obstacle detection and MTI subsystems were fully integrated into the MDARS-E system architecture, and are currently being demonstrated in fully autonomous operation.
Prime Contractor: General Dynamics Robotic Systems  
POC: Mr. Tim Matterson  
Tel Nr: 410-876-9200  
Subcontract Nr. 9610P  
Prime Contract Nr. DAAD19-01-2-0012  
The Robotics Collaborative Technology Alliance focuses on technology required to permit inanimate systems and subsystems to perform in a seemingly human fashion. It is a systems-based discipline, combining perception, plan-behavior generation, and execution in a systematic controlled fashion to achieve a designated goal with varying degrees of human interaction. To support the Army Vision of the development of the Objective Force and the Army’s role as lead service for DOD ground mobile robotics technology, the alliance focuses on enabling high-speed, autonomous mobility in unstructured environments. Sarnoff is contributing in the fields of stereo vision, fusion, scene reconstruction, and feature tracking, including UAV data georegistration and feature alignment to a UGV coordinate system.

UPI program  
Prime Contractor: Carnegie Mellon University  
POC: Lynn Young  
Tel Nr. 412-268-1206  
Period of Performance: Mar 1, 2005 - November 30, 2005

Under the UGCV-PerceptOR Integration program, Sarnoff integrated the visual odometry system developed during the DARPA PerceptOR program on the Unmanned Ground Combat Vehicle developed by the National Robotics Engineering Consortium. During evaluation experiments, inter-frame displacement measurements obtained from visual odometry were combined with orientation obtained from the UGCV INS system to provide estimates of vehicle trajectory.

2.2 Background of Key Individuals on the Princeton/Sarnoff Team

Professor Alain Kornhauser will spend 50% of his time through December 2007 as team leader. Previous to his participation in the 2005 Grand Challenge, Professor Kornhauser led Princeton’s entries in several of the early DARPA-inspired autonomous golf cart competitions in the late 1990s. He has also been a significant contributor to federally funded research efforts in Automated Highways in the late 1970’s, early 1990’s and again in the late 1990’s. He along with Professor Stengel conducted NSF funded research effort in autonomous driving and is one of the original researchers in automated transit systems dating back to the early 1970s. More recently, Professor Kornhauser is currently a leading innovator in the development of GPS-based car navigation systems.

Szymon Rusinkiewicz is part of Princeton University Computer Science department faculty and member of the Princeton Computer Graphics Group. His research concentrates on techniques that incorporate large, measured datasets of surface geometry and appearance, as well as elements of human perception. He has taught undergraduate and graduate courses on computer vision, computer graphics, scientific computing and 3-D photography over the years. His research publications can be found at his website: www.cs.princeton.edu/~smr.

Thomas Funkhouser is also part of Princeton University’s Computer Science department and a member of the Princeton Computer Graphics Group. In conjunction with Professor
Rusinkiewicz, Funkhouser has been researching shape-based recognition and analysis of 3-D models among other projects. He has also taught many undergraduate and graduate courses in the Computer Science department.

Robert Stengel is Professor of Engineering and Applied Science, Director of the Program on Robotics and Intelligent Systems, and an Affiliated Faculty Member of the Program in Quantitative and Computational Biology. His current research focuses on bioinformatics, robust control, neural networks, and intelligent systems.

Robert Schapire received his ScB in math and computer science from Brown University in 1986, and his SM (1988) and PhD (1991) from MIT under the supervision of Ronald Rivest. After a short post-doc at Harvard, he joined the technical staff at AT&T Labs (formerly AT&T Bell Laboratories) in 1991 where he remained for eleven years. At the end of 2002, he became a Professor of Computer Science at Princeton University. His awards include the 1991 ACM Doctoral Dissertation Award, the 2003 Goedel Prize and the 2004 Kanelakkis Theory and Practice Award (both of the last two with Yoav Freund). His main research interest is in theoretical and applied machine learning.

Sanjeev Kulkarni is Professor of Electrical Engineering, and an affiliated faculty member in the Department of Operations Research and Financial Engineering and the Department of Philosophy. Prof. Kulkarni’s research interests include statistical pattern recognition, nonparametric estimation, learning and adaptive systems, information theory, wireless networks, and signal/image/video processing.

Bradley Dickinson received the B.S. in Engineering from Case Western Reserve University in 1970 and the Ph.D. in Electrical Engineering from Stanford University in 1974. He is Professor of Electrical Engineering and teaches the junior project lab course which involves construction of autonomous vehicles based on 1/10 scale model car kits with single-board microcontrollers for speed control and closed-loop steering control using video cameras and other sensors.

Professor Clancy Rowley's research involves the modeling of fluid flows from a dynamical systems point of view. Specifically, he is investigating modeling and model reduction for bifurcation analysis and control; numerical methods, both for fluids simulations, and analysis of dynamical systems; and applications of geometric methods in fluid mechanics.

Patrick Cheridito is an assistant professor of operations research and financial engineering. Cheridito is emerging as a highly cited researcher in applied probability. His current research is in the area of dynamic monetary risk measures and he is inventing a new theory of second-order backward stochastic differential equations to support that work.

Alexandre d’Aspremont is an assistant professor at the department of operations research and financial engineering at Princeton University. He holds dual PhDs from the École Polytechnique and Stanford University. His research is focused on financial engineering and applications of convex programming to finance, statistics and engineering.

Dr. Harpreet S. Sawhney leads Sarnoff Corporation’s Vision Technologies Lab. Dr. Sawhney received his Ph.D. in Computer Science in Feb. 1992 from the University of Massachusetts, Amherst, focusing on Computer Vision. His areas of interest are 3D Modeling, Vision & Graphics Synthesis, Video Enhancement, Video Indexing, Data Mining and Compact Video Representations. Since 1995, he has led government and commercial programs in Immersive Telepresence, Image based 3D Modeling, Video Object Fingerprinting, Video Mosaicing, Geo-registration, 2D and 3D Video Manipulation, and Object Recognition. Dr. Sawhney was one of the key technical contributors towards the founding of two Sarnoff spinoffs, VideoBrush Inc., and Lifeclips Inc. Between 1997 and 2004, he was awarded the Sarnoff
Technical Achievement Awards seven times for his contributions in Video Mosaicing, Video Enhancement, 3D Vision and Immersive Telepresence. Between 1992 and 1995 he led video annotation and indexing research at the IBM Almaden Research Center in San Jose, CA. Dr. Sawhney has served on the Program Committees of numerous Computer Vision and Pattern Recognition conferences. He has published over 50 papers and holds 11 patents.

Dr. Garbis Salgian is a Senior Member of Technical Staff in the Mobile Vision Group in Sarnoff Corporation’s Vision Technologies Lab. He received his Ph.D. in Computer Science from the University of Rochester in 1998, with a thesis on “Tactical Driving Using Visual Routines”. His areas of interest are perception for autonomous navigation, 3D reconstruction (stereo, motion-stereo), motion detection and tracking, image fusion, image classification. He has been Sarnoff technical lead for several commercial and government projects, including PerceptOR, a DARPA program for developing perception for off-road autonomous navigation. Dr. Salgian has served as a reviewer for several Computer Vision conferences and journals. He has published 15 papers and holds 1 patent.

Christopher Broaddus is an Associate Member of Technical Staff in the Vision and Visualization Group at Sarnoff Corporation. He received his M.S in Electrical Engineering from University of Tennessee in 2005. His areas of interest are sensor and device control and system integration. He has developed sensor control architectures for controlling a network of PTZ cameras to collaboratively maintain track of multiple targets over a wide area and on-the-field camera calibration techniques for fixed and PTZ sensors. He was the team lead for the Sam Houston State Robotics Team during 2002. He received the Outstanding Graduate Student from University of Tennessee in 2004.

2.3 Involvement of Princeton University Personnel

The major thrust of this project is to be carried out by members of the Princeton University’s academic community. As such the intensity of their involvement will be substantially greater during the summer of 2007 than during the academic year. Table 2.1 below specifies the involvement by each.

<table>
<thead>
<tr>
<th>Type</th>
<th>Academic year</th>
<th>Summer 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team Leader</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>10 Faculty</td>
<td>10%</td>
<td>40%</td>
</tr>
<tr>
<td>8 Graduate Students</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>12 Undergraduates</td>
<td>20%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 2.1 Time allocation by time of year:
Princeton University

Active participation by students is an important part of this project. We are fortunate to have the six (6) most important participants in the 2005 GC be underclassmen in the fall of 2005, four of which were first semester sophomores. They are all back and devoted to active participation in the Urban Challenge. Brendan Collins’08 developed P11’s stereo vision object detection system and will lead the WorldView team under the tutelage of Professor Rusinkiewicz, Josh Herbach’08, was responsible for the simulation software during the ’05 GC and will lead the
testing team under the tutelage of Professor Vanderbei. Andrew Saxe’08 developed P11’s Command software and will lead the Command Team under the tutelage of Professor Kulkarni. Gordon Franken ’08 handled the fabrication and control of the mechanical actuators. Bryan Cattle ’07 developed and integrated all of the electronic interfaces between the computing system and the sensors and actuators on P11. He will lead the System Integration team under the tutelage of Professor Dickinson. Anand Atreya’07 was responsible for the software architecture for the ’05 GC. He will lead the Reliability group under the tutelage of Professor d’Aspremont. Additionally, Ben Essenberg’05, who was student leader of the Princeton team throughout the early development of P11 will be returning to Princeton as a graduate student and will reassume his role as student team leader. In addition to the substantial student experience available, a fresh group of students is devoting their summer to working on the preliminary phases of this project during the summer of 2006. All will be entering either their Junior or Sophomore years and are dedicated to working on this project throughout. Also, several students who will be entering Princeton in the Fall Term have expressed strong interest in contributing to this effort.
At the graduate level, each participating faculty member will assign a graduate student to research tasks in support of this effort. Finally, the participating faculty is devoted to contribute their extensive expertise to this effort. Page limits preclude our inclusion of their extensive resumes which will be provided upon request and are available at www.princeton.edu

2.3.1 Funding source for Princeton University participants

Funding of the Princeton University effort will be shared by DARPA and Princeton. This proposal is requesting funds for personnel to the extent shown in Table 2.2. Table 2.3 lists the support that will be provided by Princeton University.

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>DARPA Funded</th>
<th>Sarnoff Funded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harpreet Sawhney</td>
<td>Overall direction</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Garbis Salgian</td>
<td>Technical lead</td>
<td>33%</td>
<td></td>
</tr>
<tr>
<td>Christopher Broaddus</td>
<td>Integration and testing</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Taragay Oskiper</td>
<td>Algorithm development</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Feng Han</td>
<td>Algorithm development</td>
<td>5%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 2.4 Funding allocation for Sarnoff Personnel

2.4 Roles and Involvement of Sarnoff Personnel

The Sarnoff team will be responsible for the vision sensing subsystem. Garbis Salgian will be the technical lead for the overall effort, while Christopher Broaddus will lead the integration and testing activity. Harpreet Sawhney will provide overall direction and guidance. Other members of the team are: Taragay Oskiper – has been a key algorithm developer for robust visual odometry systems for different platforms; and Feng Han – key algorithm development for object classification algorithms for pedestrians and vehicle detection.

Table 2.4 lists the involvement of each Sarnoff team member as percentage of their time spent on the DARPA Grand Challenge project for the 18 month period August 2006 – Dec 2007

2.5 Forrestal Campus Test Facility

To achieve reliability, Princeton University intends to pursue an aggressive and systematic testing strategy. The testing group will be responsible for overseeing an incremental testing plan. The team will build test scaffolding and automation tools to verify proper handling of boundary conditions and conduct stress tests. The testing team will ensure modules are written defensively, with appropriate pre- and post-condition checking, assertions, and exception handling. The testing team will also prepare a physical test sites at Princeton’s Forrestal Campus, see Figure 2.1. Much of this site is very underutilized. It contains over 2 miles of roads, and is within several minutes of the main Princeton campus. Features already present and can be used for testing include paved and unpaved roads, 3- and 4-way intersections, parking lots with...
marked and unmarked parking spaces, a variety of lane markings, sharp turns, dead ends, differing road widths and different road boundaries (curbs, grass, dirt, etc.). Road blocks, additional lane markings and stop lines can be added to the site. The combination of Princeton University and Sarnoff’s current technologies should yield a site-visit capable vehicle rapidly, allowing for the extensive testing necessary in robotic development.

2.5.1 Physical Testing

Actuators and their control loops will be carefully tested as they are installed. This testing phase will take place at both the garage and the Forrestal Campus. A graphical testing interface will be implemented, which will allow a human in the driver seat to quickly program in specific behaviors to be tested (i.e. turn left 20 degrees and accelerate to 30 mph). This will allow us to comprehensively study the response of the control system to normal as well as boundary Command requests. Testing with a human in the vehicle will only be undertaken after a switch has been installed to hand control back to the human driver, and after a reliable e-stop is in place.

Once a working Command system has been designed and tested in the simulation environment, the vehicle will be brought to the Forrestal Campus for thorough full-system testing. This testing phase will begin with simple obstacle avoidance and lane-following trials. Lane-following will be examined with a variety of lane markings and road edges. Obstacle avoidance testing will start with a single static object in a parking lot, and work up to dynamic obstacle avoidance/trailing in a lane. When appropriate behavior has been demonstrated in the case of lane-following with a dynamic obstacle, testing will shift to more complicated traffic situations. Multiple moving obstacles will be provided by student-driven cars. This testing will begin with the execution of specific maneuvers under varying traffic situations (i.e. making a lane change with no traffic, and then doing so with a test car driving in the desired lane). After all maneuvers have been thoroughly tested and debugged, we will move to the general case of urban driving. This will be achieved by providing a mock RNDF and MDF in the same format as the DARPA-provided files, and by creating a wide range of traffic scenarios at various points on the map network. The behaviors examined in this testing phase will be twofold. First, the results of the dynamic route planner will be studied. Second, maneuver selection will be carefully examined. During this phase, certain maneuver selection scenarios will also be isolated to fine-tune the stochastic parameters and thresholds in the Command module. During all full-system testing, a human driver will be behind the wheel of Prospect Ten with the capability to instantly switch the vehicle to human-driver mode, or hit the e-stop button.
3 Management and Funding Plan

3.1 Personnel Plan
Daily management of the entire project will be done by the team leader, Prof. Alain Kornhauser. Prof. Kornhauser has been granted a sabbatical leave from teaching for the 2006-07 academic year and will thus have the proper amount of time to devote to this project. He will be primarily responsible for ensuring the proper coordination between the major sub contractor, Sarnoff Corp. and Princeton University. Since Sarnoff’s main contribution to the project is in the area of Vision, he will be assisted by Prof. Rusinkiewicz who is responsible for creating an appropriate data representation of the urban driving environment. Management of the Princeton effort will be distributed to each of the ten (10) collaborating faculty members, each of whom is responsible to not only deliver their piece but also ensure that their piece fits in with each of the others. This collaborative approach is not only common at Princeton, but is highly encouraged. Each faculty member is responsible for the students that in the end perform much of the work. While there is a formal reporting structure up to the chain, the students are encouraged to also collaborate, share and learn.

3.2 Task Breakdown & Milestone Schedule

3.2.1 Vision Tasks
Phase 1 (Planning & Vehicle Integration Support)
DARPA Funded Tasks:
- Sensor recommendations
- Evaluation of sensors and FOV
- Support for Milestone 1
Internal Funded Tasks
- None

Phase 2 (Sensing for Basic Urban Mobility)
DARPA Funded Tasks:
- Support Data Collection for Algorithm Enhancement
- Customization and Enhancement of Lane Tracking
- Customization and Enhancement of Obstacle Detection
- Detection of intersections and stop lines
- Integration, Testing and Support for Milestone 2
Internal Funded Tasks
- Develop Road Edge Finding
- Develop obstacle and road sign classification and tracking

Phase 3 (Sensing for Advanced Urban Mobility)
DARPA Funded Tasks:
- Enhance parking lot obstacle detection
- Develop parking spot detection
- Enhance obstacle detection for traffic merge and turning at intersections
- Integration, Testing and Support for Milestone 3
Internal Funded Tasks
- Enhancing IMU and GPS navigation with visual odometry

Phase 4 (Support for qualifications and final competition)
DARPA Funded Tasks:
- Integration, Testing and Support for Milestone 4 and final competition
Task List:

1. Improve and test each of the P10 Control Systems
   - Steering Control System
   - Nominal Braking System
   - Emergency Braking System (E-Stop)
   - Gear Change system
2. Codify California Rules of the Road & Traffic Regulations
3. Develop Simulation Environment
   - Build 3D Graphical Urban road Editor
   - Build Vehicle simulator
   - Build Vision System simulator
   - Build Command Module Editor
   - Model California Rules of the Road
4. Extend Vision system
   - Install rear facing cameras
   - Install front panorama Cameras
   - Install side viewing Cameras
   - 4.4 Install Blind-spot proximity sensors
5. Implement Command System
   - Enhance basic lane keeping and stationary object avoidance
   - Simulate, implement and test moving object avoidance
   - Simulate, implement and test Lane Change and Overtaking system
   - Simulate, implement and test Stop, Look and Proceed maneuver
   - Simulate, implement and test K-turn maneuver
   - Simulate, implement and test Back-up Maneuver
6. Implement Object recognition and classification system
   - Develop and test Road sign identification system
   - Develop and test Pedestrian identification system
7. Write 1st technical report
8. Milestone 2
9. Integrate Command System
10. Write Final Technical Paper
11. Milestone 3 + 4
12. Novel Approaches
    - Bio-inspired vision
    - Application of PCA to Image Classification
    - Risk Measure approaches to Command
    - New Approaches to Reliability
    - Learning and Adaptation
    - Classification
    - Recognition
<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Qtr 3</th>
<th>Qtr 4</th>
<th>Qtr 1</th>
<th>Qtr 2</th>
<th>Qtr 3</th>
<th>Qtr 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Start</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Improve and Test PMO Control Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Steering Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Nominal Braking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Emergency Braking (e-stop)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Gear Changing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Develop Simulation Environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3D Graphical Road Editor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Command Module Editor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Vision Simulator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Qualify and Model Rules of Road</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Vehicles Simulator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Milestone 1: Kickoff Meeting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Basic Operational Vision System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Evaluate and Install Full FOV Cameras</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Install Blind Spot Proximity Sensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Integrate Road Awareness Module</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Obstacle Detection and Tracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Vehicle Localization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Integrate Sensing Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Fully Functional Vision System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Advanced Obstacle Classification Research</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Advanced Obstacle Detection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Enhanced Vehicle Localization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Implement and Test Command System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Lane Keeping and Static Obstacle Avoidance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Moving Obstacle Avoidance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Lane Change and Overtaking Maneuvers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Intersection Behavior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>K-Turn and Back Up Maneuvers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Advanced Maneuvers (parking, traffic jam, etc.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Write First Technical Paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Milestone 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Technical Paper Due</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Site Visit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Milestones 3+4: NQE and Final Event</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Write Final Technical Paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3 Costs
Intentionally Left Blank
Urban Challenge contract funding will be used to fund integration and testing effort under each phase. Sarnoff internal investment funding will be used to fund technology refinement.

Phase 1: Planning and Vehicle Integration Support

Sub-Task 1.1 Write Development Plan
Refinement of the development plan as outlined herein will be performed to account for the logistics of integration and testing, and the detailed interfaces between the sensing and control systems. Sarnoff will assist with the development of this plan.

Sub-Task 1.2 Write Test Plan
A detailed test plan will track all required system behaviors, including manual operation, safety and autonomous urban navigation, between the DARPA provided documentation and the development plan. This test plan will detail the scheduled test dates and performance criteria for each test. Sarnoff will assist with the development of this plan.

Sub-Task 1.4 Purchase and installation of sensors (Princeton)
Sarnoff shall recommend sensors.

Sub-Task 1.5 Evaluate sensors and FOV (Sarnoff)
Sarnoff shall evaluate the sensors and their placement on the robot on-site. Sarnoff shall also verify that the field-of-view (FOV) covered by the sensors is sufficient to perform the basic and advanced mobility tasks as required by DARPA for the Urban Challenge.

Sub-Task 1.6 Support Milestone 1 Preparation (Sarnoff)
Sarnoff shall support Milestone 1 preparation by a) providing sample video of existing technology that will be applied and extended to the Urban Challenge, and b) providing information to Princeton for the overall system development and testing plans.

Sub-Task 1.5 Kickoff Meeting and Demonstration
This sub-task concludes with the first milestone established by DARPA. Sarnoff will attend and assist at the Kickoff Meeting and Demonstration as mutually agreed with Princeton.
Phase 2: Sensing for Basic Urban Mobility

Sub-Task 2.1 Data Collection (Sarnoff)
Sarnoff and Princeton shall, within 30 days of the start of this task, define a set of scenarios for which video, vehicle, GPS and IMU data from the automated vehicle will be recorded and used for system development.

Sub-Task 2.2 Road Awareness (Sarnoff)
Sarnoff shall integrate their existing road awareness modules into the software system developed for the Urban Challenge and test it on data acquired in Sub-Task 2.1. These modules will be enhanced to handle traffic circles and unpaved roads.

Sub-Task 2.3 Obstacle Detection, Classification & Tracking (Sarnoff)
Sarnoff shall refine and integrate existing obstacle detection algorithms, and object classification techniques into the software system developed for the Urban Challenge. Obstacle detection, classification and tracking shall be performed for forward-looking, side-looking and rear-looking sensors on an as-needed basis. The objective for this phase of obstacle detection, classification and tracking is to support the basic navigation and traffic requirements as listed in Urban Challenge PIP.

Sub-Task 2.4 Vehicle Localization and Navigation Support (Sarnoff)
Sarnoff shall integrate existing Visual Odometry software into the Urban Challenge software system. Specifically for the program, to handle GPS-denied areas, Sarnoff will improve the performance of visual odometry to achieve errors of only 5% of the distance traveled. Constraining the vehicle to lie within lanes and road edges will help to bound drift.

Sub-Task 2.5 Integrate sensing components (Sarnoff)
Sarnoff shall integrate the sensing components in Sub-Tasks 2.2, 2.3 and 2.4 into software components that will interface with the sensors mounted on the vehicle and Princeton’s learning, planning and control modules.

Sub-Task 2.15 Write Technical Paper
Sarnoff will assist with preparation of the Technical Paper.

Phase 3: Sensing for Advanced Urban Mobility

Sub-Task 3.1 Obstacle Detection, Classification and Tracking
Sarnoff shall refine the obstacle detection, classification and tracking system developed in Sub-Task 2.3 to specifically do the following: a) detect obstacles in the presence of clutter when the robot is in parking lots or other “zones” as defined by DARPA, b) detect negative obstacles (pot-holes) that are of sufficient size to damage the robot, c) identify parking spots, d) provide sufficient information to allow Princeton’s learning and planning system to determine whether a path is fully or partially blocked, and e) detect obstacles when the robot is merging in traffic or turning at an intersection. The objective
3.4 Funding Plan
Funding for the will come from DARPA support of this proposal, unrestricted endowment funds from Princeton University and in-kind services and donations. Funds amounting to $1 million are being sought from DARPA. Half will be used to support innovative research and development at Princeton University focused on improving the robustness and reliability of vision-based autonomous travel. The other half will be used to apply and expand Sarnoff Corporation’s vast experience in computer vision to this effort. Princeton University is devoting substantial in-kind services in the form of faculty and support staff time and unrestricted endowment funds to this effort.

Unrestricted Endowment Funds committed to the effort Sources include:
- CSX Transportation Research Fund: $50,000 (available through Dec 2007)
- Lion Senior Thesis Fund: $5,000 (available through December 2007)
- Union Pacific Graduate Fellowship and the Kornhauser-Gervasio Graduate Fellowship: support for 3 grad students for 1.5 academic years each.

Princeton University will also make available the complete vehicle and all intellectual and physical property associated with the Prospect Eleven vehicle and Princeton’s participation in the 2005 Grand Challenge. Additionally Princeton will make available a 1998 Chevy Metro that has previously been used for autonomous vehicle research. Finally, Princeton University will seek additional contributions as needed from independent corporations and individual donors; one such donation is expected to be another vehicle.

3.5 Export Laws and Regulations
Export Laws and Regulations are not applicable to this effort.