

Toward Smart Automotive Headlights for Safe Driving

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1. The Problem and Relevance

The long-term goal of the project is to develop the next generation headlights for vehicles, that are programmable, multi-task, react to the road environment and enhance driver safety. These smart headlights will better illuminate the road, spotlight obstacles, signs and lanes, project directions on the road, reduce glare and increase visibility in dangerous rain and snowstorms. The U.S. National Highway Safety Administration reports that annually hundreds of thousands of crashes and thousands of fatalities happen during rain and snowstorms at night. The additional cost of the headlight will be small (a few hundred dollars per vehicle at high volumes) compared to the direct and indirect savings due to reduced crashes. The project has strong commercialization potential, with vehicle exterior lighting becoming more and more adaptive recently. For 2013, the goal is to design and build an initial prototype headlight with high-speed reaction capability and algorithms for better and safer driving experience. This prototype is tested in the laboratory and outdoors.

1.1 Motivating Statistics on Highway and Driving Safety

The National Highway Safety Administration issues crash related statistics yearly [10][11][12]. A significant number of crashes occur at night and in bad weather when vehicular headlights are mandated. Below is a summary of statistics that have motivated our project:

- *2011 Crash Summary:* In 2011, there were 5,338,000 police reported crashes resulting in 29,757 fatalities and 1,530,000 injuries at an estimated economic cost of \$230.6 billion [10].
- *Evening and Night:* More than half (15,007) of vehicle fatalities and 31.4% (481,000) of vehicle injuries occurred during the evening and night. Despite 25% less travel during these times, the fatality rate per vehicle mile of travel is about three times higher than during the day [10].
- *Animals, Pedestrians, and Cyclists:* In the same year, there were 256,000 crashes with animals, 69,000 crashes with pedestrians, and 51,000 crashes with pedal cyclists. Pedestrian fatalities accounted for 13.8% of all fatalities [10].
- *Rain When Dark:* Of the 526,000 crashes caused by rain in 2011, 202,000 (38%) occurred during the evening and night. 54% (1,087) of fatal crashes caused by rain occurred during the evening and night [10].
- *Snow and Sleet When Dark:* Of the 199,000 crashed caused by snow or sleet in 2011, 88,000 (44%) occurred during the evening and night. 51% (305) of fatal crashes caused by snow or sleet occurred during the evening and night [10].
- *Headlight Glare:* In a study consisting of 873 participants, 31% of respondents found glare from oncoming vehicles noticeable and disturbing and 30% found glare from following vehicles noticeable and disturbing [11]. Using 2011 stats for nighttime fatalities, it is estimated that 450 fatalities were due to glare [12].

2. Approaches and Methodology

2.1 Background

The traditional headlight consists of a set of lamps and simple optics to direct the light beam onto the road. Vehicle manufacturers have begun developing brighter, energy efficient (LEDs [1,2,3], lasers [4]) and more advanced forward lighting systems that adjust their brightness in response to changing driving conditions. Some systems, e.g. Lincoln [5],

Audi [6], BMW [7], Volkswagen [8], mechanically swivel the headlight left or right based on the vehicle's turning radius allowing drivers to see around curved roads. Other systems allow drivers to use high beams to maximize visibility without blinding oncoming drivers, e.g., Mercedes [9]. These advanced systems have come a long way from standard headlights to improve driver visibility and enhancing safety, but fundamental issues remain: they are not versatile and are designed for one-off applications, require mechanical components reducing reliability, and do not adapt to a variety of road conditions and situations.

2.2 New Headlight Design for Adaptive and Reactive Illumination

We have developed a new smarter design for the headlight that can be programmed to react to the road environment. With this single design, road curves can be illuminated without mechanically moving the headlight, high beams can remain on without blinding oncoming traffic, and road hazards, pedestrians, and traffic signs can be spotlighted. Bad weather effects can also be removed from the driver's visual field. The proposed design consists of three components as illustrated in Figure 1: an imaging sensor that observes the environment, a processor that processes the captured visual imagery and a high-resolution spatial light modulator that controls the emitted headlight beam. The imaging, processing and lighting units are tightly integrated in a closed-loop so that the system can operate reliably at highway speeds. The spatial light modulator is a Digital Micro-mirror Device with 1024×768 pixels operating at rates of the order of kilohertz. Essentially, the headlight beam is divided into 0.7 million tiny beams each of which can be turned off or turned on for less than a millisecond. This type of modulation gives unprecedented control over the illumination, making it possible to react to every situation in the environment.

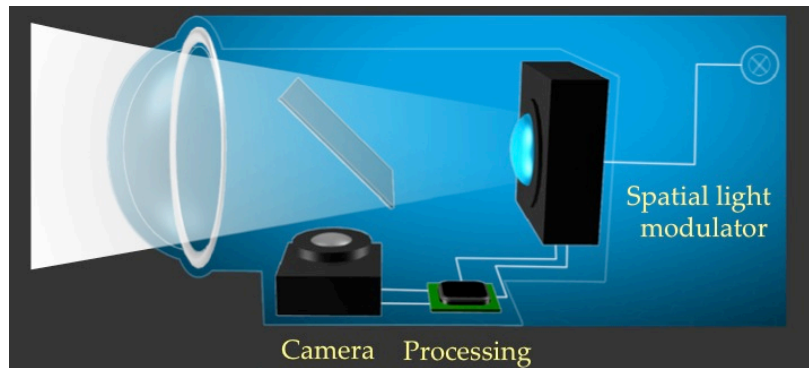


Figure 1: The conceptual design of our smart headlight, which consists of a sensor (camera) observing the road ahead and a processor to analyze captured imagery and control the headlight beam with unprecedented resolution over space (or angle) and time. The camera and the headlight are subjected to the same optical line of sight using a beam splitter. This colocation makes it unnecessary to know the distances of objects in front of the car.

2.3 Prototype

The smart headlight prototype was built with components purchased off-the-shelf, which were modified for integration (Figure 2). The camera captures images of the environment. The desktop computer manages the data input and outputs, and performs analysis on images captured by the camera. Patterns of illumination and dis-illumination are output to a spatial light modulator (DLP projector). The beam splitter (50T/50R from Edmund Optics)

optically co-locates the camera and spatial light modulator virtually placing the image sensor and DMD chip at the same location. Co-location eliminates the need to perform costly computations for determining feature correspondences and depth estimation.

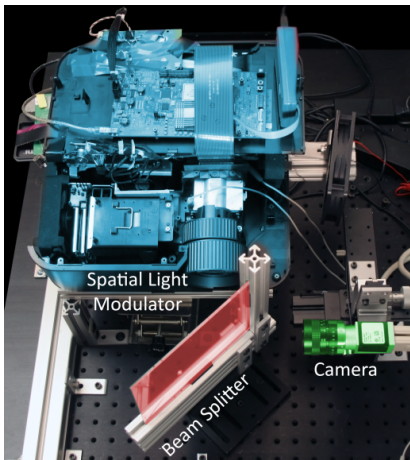


Figure 2: Prototype of the smart headlight system built with off-the-shelf components. To create the high-speed spatial light modulator a DLP projector was retrofit with a DLP development kit for high-speed streaming of illumination patterns from a desktop computer. A bulk of the native DLP projector remains to power the lamp, but only the optics and lamp are being used.

Camera: A Basler scan camera (ace acA2040-180km) with a global shutter was used. The primary reasons for choosing this camera model were based on image quality and speed. The camera utilizes a state of the art CMOS sensor (CMOSIS CMV4000) that is optimized for low-light conditions. The frame rate at full resolution (2048 x 2048 pixels) is 180 FPS and can be increased up to 11,600 FPS by reducing the vertical resolution. A monochromatic sensor was chosen to avoid the computations needed to process the Bayer pattern from a color sensor. The camera uses an extended Full Camera Link configuration to achieve high-speed data transfer. With an 82 MHz pixel clock and an 80-bit data path, 6.8 gigabits of data can be transferred per second. To further increase data transfer speed to the desktop computer, we use a PCI express frame grabber (Bitflow Karbon KBN-PCE-CL4-SP) that transfers data directly into the computer's memory rather than buffering the image.

Desktop Computer: A computer was custom built using an Intel Core 3.4GHz (i7000-2600K) CPU with eight cores and hyperthreading technology. The Asus motherboard (E6308_P8P67_PRO) has a PCI-express 2.0 bus to take full advantage of the high-speed frame grabber.

Spatial Light Modulator: A DLP projector is used as a spatial light modulator. Consumer DLP projectors are driven by video input, which constrains the maximum frame rate to far less than our goal of exceeding a modulation rate of 1 kHz. To achieve faster modulation rates a DLP development kit (WinTech W4100) based on the Discovery 4100 Development Kit (Texas Instruments) was used as the basis of our modulator. The DLP kit includes a DMD chip and a driver board. The DMD is based on the 0.7" XGA (1024 x 768) chipset and has a maximum binary pattern rate of 32,000 times per second. The driver board has a programmable FPGA (Xilinx Virtex 5) and a USB 2.0 port for receiving

input illumination patterns from the desktop computer. The FPGA was successfully programmed to stream patterns faster than 1 kHz.

The DLP kit does not include optics. Rather than design our own optics components, we retrofit a consumer DLP projector (InFocus IN3124) with the DLP kit (Figure 3). The IN3124 was chosen because it has a high output (4800 Lumens) and uses the same chipset as the DLP kit. The DLP projector was first carefully disassembled. Then the DMD chip was affixed to the optics module of the DLP projector with a custom machined mount. The aluminum heat sink was replaced with a copper heat sink and a fan was added to improve heat dissipation.

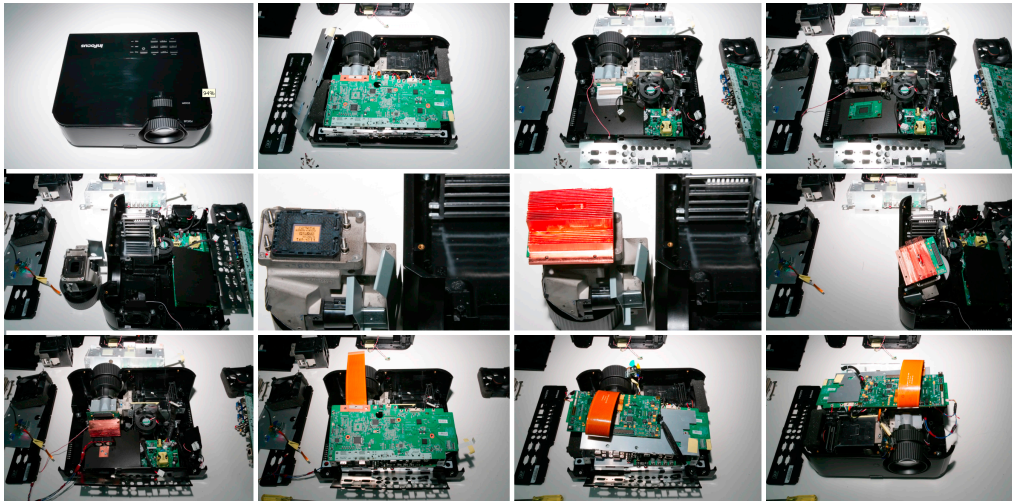


Figure 3: From top left to bottom right shows retrofitting a DLP projector with a DLP development kit. The native DMD chip was removed and replaced with the DMD from the DLP development kit. An additional fan and copper heat sink was added to improve heat dissipation.

In single chip DMD DLP projectors, temporal dithering with a color wheel is utilized to display color. An artifact of temporal dithering is the visibility of color sequences even when displaying white light. To avoid this visual annoyance, the color wheel was removed from the optical path and mounted elsewhere to maintain operability. All of the electronic boards were also left attached to maintain operability even though only optics and lamp are actively used.

Performance: The prototype's operation is pipelined in three parallel stages; image capture, image processing, and projection (Figure 4). The execution time for each stage was assessed with high precision time measurement on the desktop computer and an oscilloscope. The first stage takes about 1.0 ms; 0.4 ms to expose the image sensor and 0.6 ms to transfer the entire image to the computer. The second stage requires 0.3 ms for image processing and 0.7 ms for transferring the illumination pattern to the spatial light modulator. Displaying the illumination pattern occurs in the third stage. The DMD can be reset very quickly (immeasurable) after receiving data from the computer, therefore, the total latency of the system is the aggregate of the first two stages, 2.0 ms. The latency can be reduced by shortening the exposure time and reducing the resolution of the image.

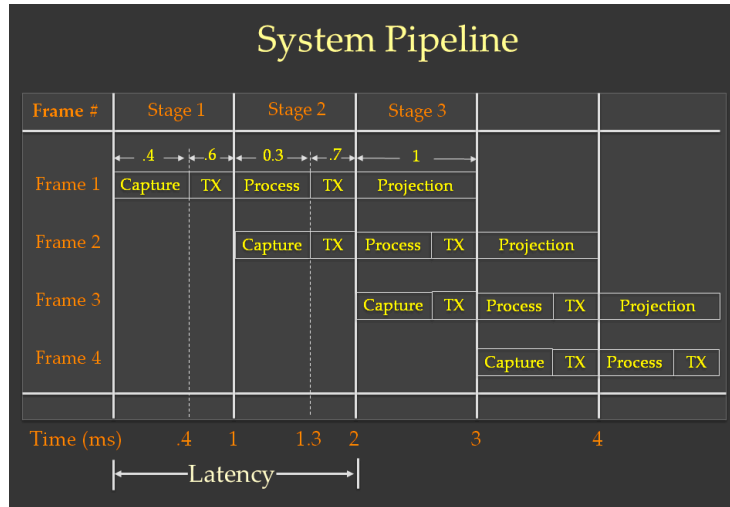


Figure 4: The smart headlight system is pipelined into three parallel stages; image capture, image processing, and light projection. Image capture and processing determine system latency because projection occurs as soon as the pattern is received. Reducing exposure time and reducing image resolution in the vertical direction can improve latency.

2.4 Anti-Glare Capable High Beams

The AAA safety research mentions that a 55-year old takes 8 times longer to recover from glare as compared to a 16-year old. Glare from the headlight beams (in particular high beams) of oncoming vehicles cause significant stress and distraction at best and temporary blindness at worst. Trucks and other vehicles with headlights at high positions are the worst offenders for glare. High beams on the other hand allow wider and better visibility in curvy one-lane roads and in particular avoid road-kills due to animals jumping in front of the vehicle or pedestrians crossing the roads from the sidewalks. Our headlight design allows us to enable high beams to be used at any time the driver needs but without glaring any other driver on the road.

The problem and idea is illustrated in Figure 5. The camera in the headlight captures images and the processor identifies oncoming vehicles based on their bright headlights. Once the locations of the vehicles are known in the camera's reference frame, it is transformed to the headlight reference frame and the spatial light modulator blocks or reduces light in that direction. Since the resolution offered by the modulator is very high, only a small beam angle corresponding to the oncoming driver's head is blocked. This type of blocking of the beam can be done for any number of oncoming drivers. The view from the smart headlight enabled car is illuminated with the high beam with small spots of darkness in regions of the oncoming vehicles. Since the spots are more or less defocused, the driver does not notice them.



Figure 5: Illustrating the problem and solution for glare from headlights. Glare can cause temporary blindness when driving that can lead to catastrophic accidents. The smart headlight system identifies the oncoming drivers and reduces the intensity to a small region covering each driver on the road. The driver of the smart headlight enabled vehicle is then free to use high beams potentially all the time without worrying about switching them.

We have conducted several experiments with our prototype within the laboratory as well as outdoors at night. Figure 6 shows two video frames captured from inside a vehicle driven towards the smart headlight. In one frame, we show the effect of the glare as the vehicle nears and in the other, we show the benefit of our anti-glare system. Clearly, the difference is significant. We have conducted several live demonstrations of this system and all drivers of the oncoming vehicle report that the anti-glare allows them to see the road clearly even when they come close to the headlight of the other vehicle. Our current prototype headlight is stationary and in the future, we will deploy it on a moving vehicle.

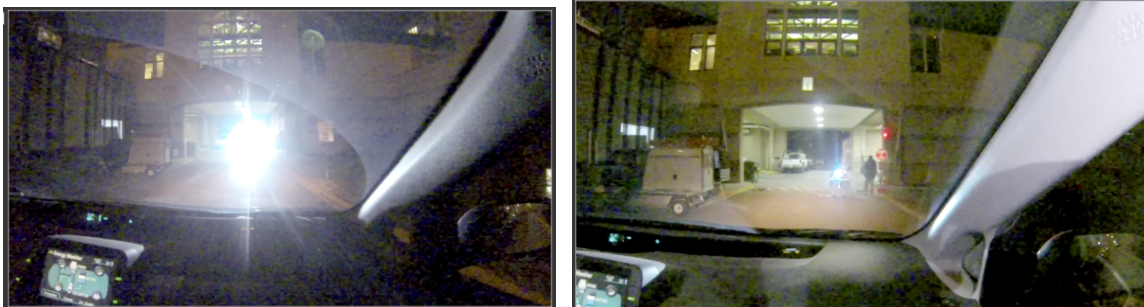


Figure 6: Results showing the effectiveness of the smart headlight system to reduce glare for the oncoming driver(s). The light toward the oncoming driver is reduced only in a small region and the smart headlight maintains its high beams everywhere else. On the left, is the glare seen when the anti-glare feature is turned off when the driver is almost blinded. On the right, the image shows the reduced glare when the anti-glare feature is turned on. Notice the road and the surrounding environment are clearly visible on the right.

2.5 Improving visibility in Rain and Snow storms

Over the past two years, we have developed a prototype that increases visibility of the driver during rain and snowstorms. The idea is to exploit the fast illumination beam control to distribute light in between falling precipitation particles (snowflakes, raindrops). Incredible as it may sound, our simulations and prototype demonstrate that the idea is quite feasible – one of our conclusions is that a strong thunderstorm will look like a drizzle leading to less stress while driving. The idea is very similar to anti-glare application where light is reduced to a location in front of the vehicle. However, this application is significantly more challenging since (a) the raindrops and snowflakes are very small compared to the easily detected oncoming vehicle, and (b) the density of precipitation is several orders higher than the number of cars on the road.



Figure 7: Driving in a snowstorm or rainstorm at night is incredibly hard. The snowflakes and raindrops are illuminated brightly and distract the driver from observing the entire road. The smart headlight has unprecedented resolution over angle and time so that beams of light may be sent in between the falling rain and snow.

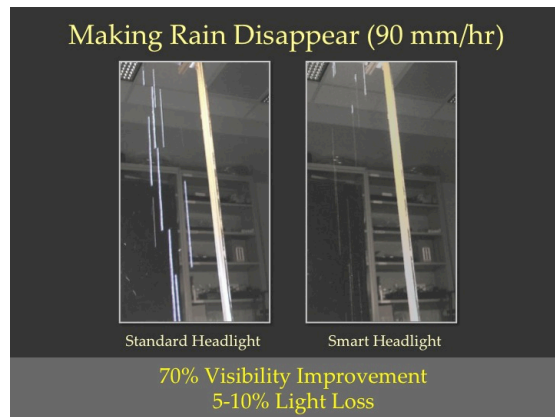
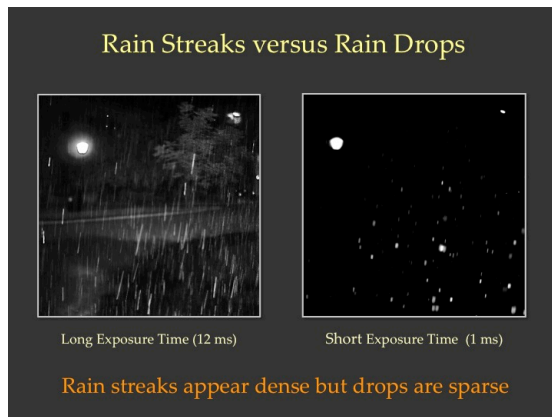


Figure 8: Is sending beams in between snowflakes and raindrops even feasible? Incredible as it sounds, the idea is feasible because there is significant empty space between snowflakes and raindrops even during a strong storm and because the headlight beams can be controlled precisely over space and time. On the left, are two images captured in a strong rainstorm with long and short exposures. The long exposures mimic the human eye giving the false illusion that rain occupies the volume densely. The prototype built is used to stream light between drops in the lab to obtain roughly 70% improvement in visibility while losing only about 5-10% of the light.

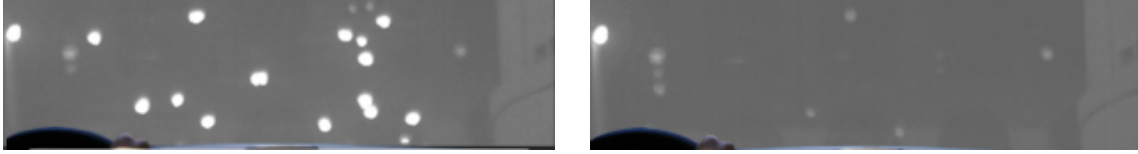


Figure 9: The results obtained for improved visibility at night during snow. Snow was artificially generated for this experiment. On the left, we see the snowflakes very brightly whereas the light beams are turned off toward the snowflakes thus reducing driver distraction. In the case of snow, we obtain about 60% visibility improvement with a slightly higher 10-15% light loss.

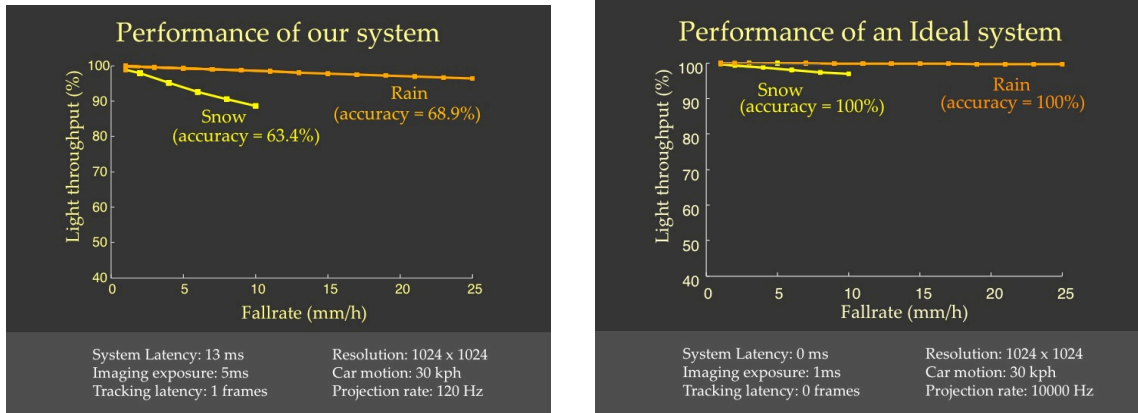


Figure 10: Simulations of our prototype system as compared to an ideal system. While our current prototype has not been mounted on a car and is not moving, the simulator can predict its behavior at any speed and for any rain and snow fall rates. The plots show the light throughput for different weather conditions. The goal is to get this light throughput as high as possible while reducing the visibility of rain or snow as much as possible.

We first built a simulator for different weather conditions and vehicle speeds [15]. This is used to determine the reaction time required for our headlight to be successful in ‘dis-illuminating’ the snowflakes and raindrops. The goal is to send as much light as possible from the headlight while not ‘hitting’ any precipitation. An ordinary headlight will have 100% light throughput and 0% accuracy in that all precipitation is illuminated. If the headlight is switched off, we will achieve 100% accuracy in that no precipitation is illuminated but at the same time the light throughput is 0%. Thus, the goal of the system is to obtain high light throughput while maintaining high accuracy.

We developed two algorithms for this system: a prediction based method and a prediction-free method. In the prediction-based method, we illuminate the precipitation for a short time and compute the particle locations and velocities. These current locations and velocities are used to predict the future locations of precipitation. The prediction time is the latency of our system – the higher the latency, the greater the prediction distance and hence more likely the error. The first prototype had a latency of more than 20 milliseconds (from image capture to illumination). This system was useful in cases where prediction is straightforward – linear prediction in the case of rain without any wind (see Figure 8) [15]. But wind and vehicle vibration and speed all make it harder to use this model to predict in

the real world. Because of this, we improved our prototype speed to have only a latency of about 2 milliseconds and the camera and illumination rates were about 1.7kHz. With this new system, it was possible to dis-illuminate snowflakes that fall in random directions due to wind (see Figure 9). In order to make this type of application possible at highway speeds and to obtain even higher visibilities (see current performance in Figure 10), we will next work toward making the system smaller without a separate computer so the data transfer latencies are reduced further.

2.6 Fusing Radar, Camera and Headlight for better visibility in Fog and Mist

While the precipitation due to rain and snow is sparse, fog and mist are very dense and streaming light in between fog/mist particles is virtually impossible. Penetration of visible light through fog is very shallow and hence visibility at night during fog is poor. For this application, we developed another prototype headlight (shown in Figure 11) that includes a Radar, a camera and a spatial light modulator. The Radar penetrates through very thick fog and returns locations of the obstacles on the road in front. These locations are then transformed to the camera and the headlights' coordinate frames using a series of three-dimensional rotations and translations (Figure 11). A better visualization for the driver is possible if the locations of the obstacles are shown in a camera captured images that are displayed to the driver. Alternatively, the same locations can be used to send small spotlights from the headlights to indicate obstacle locations to the driver's naked eye without any requirement for a display.

We have conducted several experiments with a dense fog generator similar to the one used in Hollywood movies. Figure 12 shows the result of tracking a pedestrian through dense fog. This type of visualization makes it easier for the driver to navigate through fog. We have also conducted separate research on controlling the headlight beams so that a single sliver of a light beam is swept across the field of view of the driver. A camera is synchronized to the motion of the beam and captures images sequentially. Each image that is captured has better contrast than that captured when the entire headlight is on simultaneously. All the captured images are stitched together to produce a better visibility image through fog. Our research here was funded by the Office of Naval Research and focused on murky waters. We will incorporate these ideas to our smart headlight to see through fog in front of a moving vehicle. Preliminary results are shown in Figure 12.

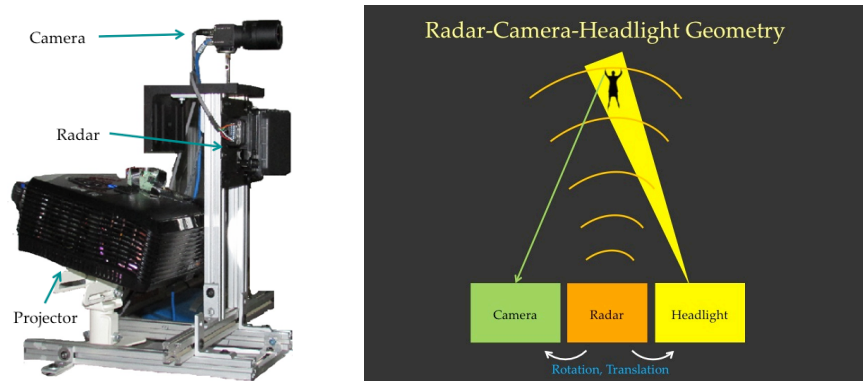


Figure 11: *Prototype and mathematics (geometry) of the system to provide better visualization of the obstacles on the road hidden in a foggy environment. The prototype*

consists of a camera, headlight (spatial light modulator of a projector) and a Radar. The coordinate systems of the three devices are related by a series of rotations and translations.

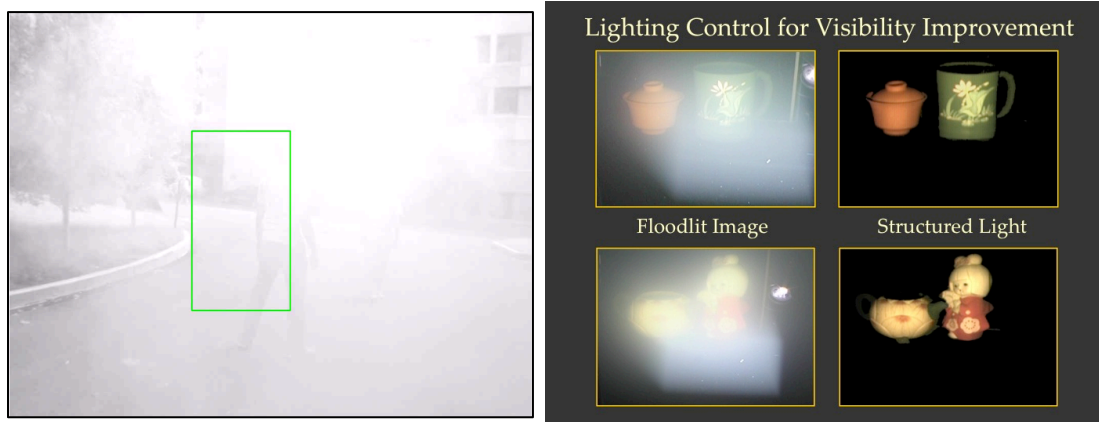


Figure 12: Results obtained for tracking pedestrians through fog and our related past research [16] funded by the Office of Naval Research to control light beams to improve visibility of murky waters. Going forward, this research will be incorporated into our smart headlight.

2.7 Fundamental Research on Object Tracking in Videos

In order to be able to identify and track arbitrary objects on the road with our smart headlight system, we investigated and developed new optimization algorithms. These algorithms are not only useful for the transportation application but more broadly to many other domains like surveillance and security as well as aid scientific understanding of materials that make up the objects in the scene. We will incorporate these methods into our smart headlight project going forward.

Hierarchical algorithm for object deformation and tracking [13]:

Real-world surfaces such as clothing, water and human body deform and move in complex ways. The image distortions observed are high dimensional and non-linear, making it hard to estimate these deformations and motions accurately. The recent data-driven descent approach we developed before applies Nearest Neighbor estimators iteratively on a particular distribution of training samples to obtain a globally optimal and dense tracking field between subsequent frames. In this work, we developed a hierarchical structure for the Nearest Neighbor estimators, each of which can have only a local image support. We demonstrate in both theory and practice that this algorithm has several advantages over the non- hierarchical version: it guarantees global optimality with significantly fewer training samples, is several orders faster, provides a metric to decide whether a given image is “hard” (or “easy”) requiring more (or less) samples, and can handle more complex scenes that include both global motion and local deformation. The proposed algorithm successfully tracks a broad range of non-rigid scenes including water, clothing, and medical images, and compares favorably against several other deformation estimation and tracking approaches that do not provide optimality guarantees.

Compensating for Motion During Direct-Global Separation [14]:

Separating the direct and global components of radiance can aid shape recovery algorithms and can provide useful information about materials in a scene. Practical

methods for finding the direct and global components use multiple images captured under varying illumination patterns and require the scene, light source and camera to remain stationary during the image acquisition process. In this work, we develop a motion compensation method that relaxes this condition and allows direct-global separation to be performed on video sequences of dynamic scenes captured by moving projector-camera systems. Key to our method is being able to register frames in a video sequence to each other in the presence of time varying, high frequency active illumination patterns. We compare our motion compensated method to alternatives such as single shot separation and frame interleaving as well as ground truth. We present results on challenging video sequences that include various types of motions and deformations in scenes that contain complex materials like fabric, skin, leaves and wax.

3. Publicity for the Project

The Smart Headlight project received strong publicity over the past year – 100+ print articles and TV news stories at top venues like BBC, PC Magazine, Engadget, Slashdot, NBC, Discovery, Wired, Popular Science. The U.S. National Science Foundation and National Academy of Engineering highlighted this project as an Engineering Innovation and have distributed radio advertisements to traffic stations across the US. Car and Driver magazine and Edmunds.com list this project as one of the top 10 most promising technologies. Two prior publications on this topic based on which this prototype was built both won Best Paper/Best Paper Honorable Mention awards. This was a featured project at an Online Automotive and Transportation tradeshow in September 2013 that showcases future technologies. The Smart Headlights also featured prominently in Keynote addresses of the Chief Technology Officer and President of Intel since Intel is providing matching funds for this project. We are currently in discussions with the National Highway Traffic Safety Administration (NHTSA) on safety and regulations with respect to adaptive exterior lighting on vehicles.

4. Findings and Conclusions

- a) The headlight should not be a passive device that can be just completely switched on or off. It should be programmable to perform many different tasks to help the driver in various road environments.
- b) The headlight design developed provides unprecedented light beam control over angle and time. Essentially, the full headlight beam can be split into hundreds of thousands of tiny little beams that can be turned on or off for very short durations (milliseconds).
- c) The flexibility and control of the headlight will allow us to perform numerous tasks for the first time: allowing drivers to use high beams without glaring any other driver on the road, allowing oncoming drivers to see the vehicle and road clearly despite the high beams, allowing drivers to see better in rain, snow and fog, and allowing better illumination so lanes, sidewalks and dividers can be visible clearly.
- d) The prototypes we have built can react to the road environment within 2 milliseconds (100 times faster reaction than an average driver) with a refresh rate of more than 1.7kHz. This refresh rate will not cause any flicker to be seen by the human eye (flicker is seen at lower rates like 30-60Hz).
- e) Further research and development is needed to make the prototype small to fit within actual vehicle headlight compartments. Further engineering is required to make the system reliable in the presence of vehicular vibrations and heat. Lastly,

further research is needed in developing reliable software for deploying this headlight on an actual vehicle moving at highway speeds.

5. Recommendations developed as a Result of the Project

- a) Illuminating as brightly as possible everywhere in front of the vehicle may not be best for all road environments and conditions. It is clear that we do not use our high beams in bad weather conditions.
- b) Adaptive exterior lighting from vehicles is important for traffic safety and U.S. government regulations must reflect this. European regulations have already begun allowing adaptive illumination on roads.

References:

- [0] <http://www-nrd.nhtsa.dot.gov/Pubs/810637.pdf>
- [1] http://www.lexus.com/hybridbrochure/ls_600h_l.html
- [2] <http://models.audiusa.com/r8>
- [3] <http://www.cadillac.com/escalade-suv.html>
- [4] <http://www.bmwblog.com/2011/09/01/bmw-develops-laser-light-for-the-car/>
- [5] <http://www.lincoln.com/crossovers/mkx/features/Feature25/>
- [6] http://www.audiusa.com/us/brand/en/tools/advice/glossary/adaptive_lighting.browser.html
- [7] http://www.bmw.com/com/en/insights/technology/technology_guide/articles/mm_adaptive_headlights.html
- [8] <http://my.vw.com/2013-cc/security/adaptive-front-lighting-system-afs>
- [9] http://www.mercedesbenz.com/Sep08/25_001417_Mercedes-Benz_Introduces_New_Adaptive_High_Beam_Assistant.html
- [10] National Highway Traffic Safety Administration, TRAFFIC SAFETY FACTS 2011: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System, 2011. <http://www-nrd.nhtsa.dot.gov/Pubs/811754AR.pdf>
- [11] National Highway Traffic Safety Administration, Report on DRIVERS PERCEPTIONS OF HEADLIGHT GLARE FROM ONCOMING AND FOLLOWING VEHICLES, 2003. <http://www-nrd.nhtsa.dot.gov/Pubs/809-669.pdf>
- [12] National Highway Traffic Safety Administration, Nighttime Glare and Driving Performance, 2007.
- [13] Hierarchical Data Driven Descent for Efficient Optimal Deformation Estimation, Yuandong Tian and Srinivasa G. Narasimhan, International Conference of Computer Vision (ICCV), 2013.
- [14] Compensating for Motion During Direct-Global Separation, Supreeth Achar, Steve Nuske and Srinivasa G. Narasimhan, International Conference of Computer Vision (ICCV), 2013.
- [15] Fast Reactive Illumination through Rain and Snow, Raoul de Charette, Robert Tamburo, Peter Barnum, Anthony Rowe, Takeo Kanade and Srinivasa G. Narasimhan, IEEE International Conference on Computational Photography (ICCP), April 2012.
- [16] On Controlling Light Transport in Poor Visibility Environments, Mohit Gupta, Srinivasa G. Narasimhan, and Yoav Y. Schechner, IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2008.