The DARPA Urban Challenge

Autonomous Vehicles in City Traffic
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STAR (Springer Tracts in Advanced Robotics) has been promoted under the auspices of EURON (European Robotics Research Network)
By the dawn of the new millennium, robotics has undergone a major transformation in scope and dimensions. This expansion has been brought about by the maturity of the field and the advances in its related technologies. From a largely dominant industrial focus, robotics has been rapidly expanding into the challenges of the human world. The new generation of robots is expected to safely and dependably co-habitat with humans in homes, workplaces, and communities, providing support in services, entertainment, education, healthcare, manufacturing, and assistance.

Beyond its impact on physical robots, the body of knowledge robotics has produced is revealing a much wider range of applications reaching across diverse research areas and scientific disciplines, such as: biomechanics, haptics, neurosciences, virtual simulation, animation, surgery, and sensor networks among others. In return, the challenges of the new emerging areas are proving an abundant source of stimulation and insights for the field of robotics. It is indeed at the intersection of disciplines that the most striking advances happen.

The goal of the series of *Springer Tracts in Advanced Robotics (STAR)* is to bring, in a timely fashion, the latest advances and developments in robotics on the basis of their significance and quality. It is our hope that the wider dissemination of research developments will stimulate more exchanges and collaborations among the research community and contribute to further advancement of this rapidly growing field.

The volume edited by Martin Buehler, Karl Iagnemma and Sanjiv Singh presents a unique and complete collection of the scientific results by the finalist teams which took part into the Urban Challenge in November 2007 in the mock city environment of the George Air Force base in Victorville, California. The book is the companion of the previous book by the same editors which was devoted to the Grand Challenge in the Nevada desert of October 2005, the second in the series sponsored by DARPA.

The Urban Challenge demonstrated how the fast growing progress toward the development of new perception, control, and motion planning techniques allow intelligent autonomous vehicles not only to travel significant distances in off-road terrain, but also to operate in urban scenarios. Beyond the value for future military applications motivating DARPA to sponsor the race, the expected impact
in the commercial sector for automotive manufacturers is equally if not more important: autonomous sensing and control constitute key technologies to vehicles of the future that might help save thousands of lives now lost in traffic accidents!

Like in the case of the previous volume, the original papers were earlier published in three special issues of the Journal of Field Robotics. Our series is very proud to reprise them and again offer archival publication as a special STAR volume!

Naples, Italy
July 2009

Bruno Siciliano
STAR Editor
It might have been the first robotic demolition derby.

Imagine a large field of vehicles without drivers traversing 60 miles in live traffic, operating entirely without human guidance. A complex course including intersections, traffic circles, and parking lots, defined by just kilobytes of data. Vehicles several meters wide traveling down lanes only slightly wider, using localization systems with an accuracy of several meters. Humans in vehicles facing full-size unmanned vehicles at approach speeds up to 60 miles per hour. Even today, this does not sound like a recipe for success.

The Urban Challenge, conducted in November, 2007, began with the vision of orderly robotic traffic—busy city streets with a mix of human and robotic drivers. It is clear that the future use of autonomous vehicles would be severely limited unless operation were demonstrably safe amidst moving traffic. A conclusive demonstration would be impossible for many other organizations, but this is precisely the type of risk that the Defense Advanced Research Projects Agency (DARPA) was created to tackle.

In the face of such long odds, the Agency’s ace card is its ultra-resourceful contractor community. It was this community of participants, who deciphered the rules, husbanded resources, and invented the way to a successful conclusion. Their technical results are set down in this special edition, but read between the lines to appreciate the magnitude of the task and the inherent risk undertaken.

The successful program outcome is really a tribute to this entire community, from the top teams who conducted tutorials in the pit area, to the intrepid groups of undergraduates who dared to compete on a shoestring. This technical community is the group that both taught one another and competed with one another to create the excellence that will be remembered as the Urban Challenge.

In the end, when the last paper is written and the best ideas are carried forward into subsequent developments, what remains is the inspiration of a group of researchers who proved to themselves and to the world what was possible with too little funds, not enough time, in pursuit of a clear and focused goal.

Congratulations to them all.

Norm Whitaker
DARPA Urban Challenge Program Manager
The 3rd DARPA Grand Challenge also known as the “Urban Challenge” almost didn’t happen. The previous challenges ended so successfully that I didn’t see a point to go onto another one. DARPA’s mission is to show that something can be done and to transition it on to other agencies and organizations for the development while we go back to determine what new technology needs to be brought forth.

But there were strong arguments to carry on; the major point was that we didn’t prove it could be done in traffic when there were both moving robotic vehicles and moving vehicles driven by people. I agreed and the Urban Challenge was born.

We decided on George Air Force base in Victorville California, which was no longer in use but still had a housing development with streets, stop signs, etc. We also decided that the evaluation would not be strictly based on speed getting through a course but that the vehicles had to obey California driving laws. In fact we decided to use the California driving test evaluation criteria as a way to distinguish between vehicles that could go fast and those that also had at least the intelligence to pass the test.

This meant that we were going to have to have people out on the track writing traffic tickets which increased greatly the danger of the event.

We had 20+ vehicles make it into the qualifying runs. They had to go through a difficult test. Not only did they have to be good technically but they also had to prove that they were safe. The safety concern culled the number of vehicles who were going to be allowed into the finals down to eleven.

I worried about what would happen the first time robotic vehicles met other robotic vehicles with no possible human intervention. This was something we couldn’t test in the qualifying runs and was a major unknown.

The nightmare happened within minutes of the start when four robotics vehicles came to a 4-way stop at the same time. I held my breath as this event unfolded.

It turned out that there wasn’t a problem. California rules state that the vehicle which arrives before yours at the stop sign has the right of way. The robotic vehicles knew the arrival order and therefore knew their turn. The robots performed perfectly. In fact, we were having trouble with the vehicles driven by humans who tended to somewhat disobey the California rules.

It was a spectacular finish. We had 6 out of the 11 starters finish and gave away all the 1st, 2nd, and 3rd prizes. I am sure this book will go into greater depth on the details.
The response from the US and the world was fantastic. We had done what we wanted to do and showed that robotic vehicles could perform, even when mixed in with each other and people driven vehicles, in a very realistic environment.

The Urban Challenge showed that a new important military capability was possible and convoys, for example, might someday not need people drivers. But as important, we had impacted the lives of tens of thousands of people who might never have gotten involved in science and engineering if it had not been for the Challenge series and learned how much fun it was.

The Challenge series may not have been the most important capability that was developed during my 8 years as DARPA Director but it was high on the list and is undoubtedly the most publicly known development since the internet. I am sure that this book will give you much more insight and details in what happened and I know you will enjoy reading it even if you were not there in person.

Anthony J. “Tony” Tether
DARPA Director, 2001-2009
The Defense Advanced Research Projects Agency (DARPA) Urban Challenge (DUC) was held on November 3, 2007, at the now-closed George Air Force Base in Victorville, California, in the United States. The DUC was the third in a series of DARPA-sponsored competitions for autonomous vehicles. Whereas the previous two “Grand Challenges” (held in 2003 and 2005) were intended to demonstrate that autonomous ground vehicles could travel significant distances in off-road terrain, the DUC was designed to foster innovation in autonomous vehicle operation in busy urban environments. Competitors developed full-scale (i.e., passenger vehicle–sized) autonomous vehicles to navigate through a mock city environment, executing simulated military supply missions while merging into moving traffic, navigating traffic circles, negotiating busy intersections, and avoiding obstacles. Race rules required that the 96 km (60 mile) course be completed in less than 6 hours. The rules also required that competitors obey all traffic regulations while avoiding other competitors and human-driven “traffic vehicles.”

The winner of the race—and of a $2 million dollar first prize—was a modified Chevy Tahoe named “Boss” developed by Tartan Racing, a team led by Carnegie Mellon University. The second-place finisher, and recipient of a $1 million prize, was Stanford Racing Team’s “Junior,” a Volkswagen Passat. In third place was team VictorTango from Virginia Tech, winning a $500,000 prize with a Ford Escape hybrid dubbed “Odin.” Vehicles from MIT, Cornell, and the University of Pennsylvania/Lehigh also successfully completed the course. It should be noted that these 6 teams were winnowed down from an initial pool of 89 teams that were initially accepted for participation in the DUC. Three months before the race, a panel from DARPA selected 35 teams to participate in the National Qualifying Event (NQE), which was held one week before the final race. Field trials at the NQE narrowed the field down to the 11 teams that competed on race day.

It can be argued that the greatest achievement of the Urban Challenge was the production of important new research in perception, control, and motion planning for intelligent autonomous vehicles operating in urban scenarios. Another long-term result of the DUC is the undeniable shift in public perception that robotic systems are now able to successfully manage the complexities of an urban environment. Although the race’s mock city environment simplified some of the
challenges present in a real urban environment (e.g., there were no pedestrians or traffic signals), the race left no doubt in the minds of most observers that the development of vehicles that can “drive themselves” in real-world settings is now inevitable.

Although DARPA’s direct motivation for sponsoring the race was to foster technology for future military applications, a nearer term impact may lie in the commercial sector. Automotive manufacturers view autonomous sensing and control technologies as keys to vehicles of the future that will save thousands of lives now lost in traffic accidents. Manufacturers of mining and agricultural equipment are also interested in creating a next generation of vehicles that will reduce the need for human control in dirty and dangerous applications. Clearly, if the technology displayed at the DUC can be made inexpensive and robust enough for use in the commercial sector, the effect of the Urban Challenge on society will be substantial and long lasting. For this, the robotics community is beholden to DARPA for providing both critical resources and a well-designed evaluation process for the competition.

This book presents 13 papers describing all of the vehicles that competed as finalists in the DUC. These papers initially appeared in three special issues of the Journal of Field Robotics, in August, September, and October 2008. They document the mechanical, algorithmic, and sensory solutions developed by the various teams. All papers were subjected to the normal Journal of Field Robotics peer review process. Also included in this volume is a new picture gallery of the finalist robots, with a description of their individual race results, and forewords by Norm Whitaker, the DARPA program manager who oversaw the Urban Challenge contest, and Tony Tether, who served as DARPA’s director from 2001-2009.

The first paper, Tartan Racing’s “Autonomous Driving in Urban Environments: Boss and the Urban Challenge” by Urmson et al., is a comprehensive description of Boss. The paper describes Boss’s mechanical and software systems, including its motion planning, perception, mission planning, and tactical behavior algorithms. The software infrastructure is also detailed. Testing, performance in the NQE, and race performance are also documented. Boss averaged 22.5 km/h during the race and completed the course with a winning time of 4 hours and 10 minutes. A companion paper, “Motion Planning in Urban Environments,” by Ferguson et al., offers more detail about Boss’ planning system, which combines a model-predictive trajectory generation algorithm for computing dynamically feasible actions with two higher-level planners for generating long-range plans in both on-road and unstructured regions of the environment.

The next paper, “Junior: The Stanford Entry in the Urban Challenge” by Montemerlo et al., focuses on Stanford’s software and describes how Junior made its driving decisions through a distributed software pipeline that integrated perception, planning, and control. The paper illustrates the development of a robust system for urban in-traffic autonomous navigation, based on the integration of recent innovations in probabilistic localization, mapping, tracking, global and local planning, and a finite state machine for making the robot robust to unexpected situations. Also presented are new developments in obstacle/curb detection, vehicle tracking, motion planning, and behavioral hierarchies that
address a broad range of traffic situations. The paper concludes with an analysis of notable race events. Junior averaged 22.1 km/h during the race and completed the course with a second-place time of 4 hours and 29 minutes.

Team VictorTango’s entry into the DUC is described in the paper “Odin: Team VictorTango’s Entry in the DARPA Urban Challenge” by Bacha et al. An overview of the vehicle platform and system architecture is provided, along with a description of the perception and planning systems. A description of Odin’s performance in the NQE and race is also provided, including an analysis of various issues faced by the vehicle during testing and competition. Odin averaged just under 21 km/h in the race and completed the course in third place with a time of 4 hours and 36 minutes.

The paper, “A Perception-Driven Autonomous Urban Vehicle,” from the MIT team, describes the architecture and implementation of a vehicle designed to handle the DARPA Urban Challenge requirements of perceiving and navigating a road network with segments defined by sparse waypoints. The vehicle implementation includes a large suite of heterogeneous sensors with significant communications and computation bandwidth to capture and process high-resolution, high-rate sensor data. The output of the perception system is fed into a kinodynamic motion planning algorithm that enables driving in lanes, three-point turns, parking, and maneuvering through obstacle fields. The intention was to develop a platform for research in autonomous driving in GPS-denied and highly dynamic environments with poor a priori information. Team MIT’s entry successfully completed the course, finishing in fourth place.

“Little Ben: The Ben Franklin Racing Team’s Entry in the 2007 DARPA Urban Challenge” by Bohren et al. details the sensing, planning, navigation, and actuation systems for “Little Ben,” a modified Toyota Prius hybrid. The paper describes methods for integrating sensor information into a dynamic map that can robustly handle GPS dropouts and errors. A planning algorithm is presented that consists of a high-level mission planner and low-level trajectory planner. A method for cost-based actuator level control is also described. Little Ben was one of the six vehicles that successfully completed the Urban Challenge.

The paper “Team Cornell’s Skynet: Robust Perception and Planning in an Urban Environment” by Miller et al. describes Team Cornell’s entry into the DUC, detailing the design and software of the autonomous vehicle Skynet. The article describes Skynet’s custom actuation and power distribution system, tightly coupled attitude and position estimator, novel obstacle detection and tracking system, system for augmenting position estimates with vision-based detection algorithms, path planner based on physical vehicle constraints and a nonlinear optimization routine, and a state-based reasoning agent for obeying traffic laws. The successful performance of Skynet at the NQE and final race are also described.

“A Practical Approach to Robotic Design for the DARPA Urban Challenge” by Patz et al. describes the journey of TeamUCF and their “Knight Rider” during the Urban Challenge. Three of the only five core team members had participated in the 2005 Grand Challenge. This team’s success is all the more impressive when considering its small size and budget. Sensor data were fused from a Doppler
radar and multiple SICK laser scanners. Two of those scanners rotated to provide 3-D image processing with both range and intensity data. This “world view” was processed by a context-based reasoning control system to yield tactical mission commands, which were forwarded to traditional PID control loops.

The next paper, “Team AnnieWAY’s Autonomous System for the DARPA Urban Challenge 2007,” describes Team AnnieWay’s minimalistic approach that relied primarily on a multibeam Velodyne laser scanner mounted on the rooftop of their VW Passat, and just one computer. The laser scanner’s range data provided 3D scene geometry information, and the reflectivity data allowed robust lane marker detection. Mission and maneuver selection was conducted via a hierarchical state machine. The reactive part of the system used a precomputed set of motion primitives that vary with the speed of the vehicle and that are described in the subsequent paper, “Driving with Tentacles: Integral Structures for Sensing and Motion” by von Hundelshausen et al. Here, motion primitives (tentacles) that Team AnnieWAY used for both perception and motion execution are described. In contrast to other methods, the algorithm uses a vehicle-centered occupancy grid to avoid obstacles. The approach is very efficient, because the relationship between tentacles and the grid is static. Even though this approach is not based on vehicle dynamics, the resulting path errors are shown to be bounded to obstacle-free areas.

“Caroline: An Autonomously Driving Vehicle for Urban Environments,” describes the architecture of a system comprising eight main modules: sensor data acquisition, sensor data fusion, image processing, digital map, artificial intelligence, vehicle path planning and low-level control, supervisory watchdog and online-diagnosis, and telemetry and data storage for offline analysis. Detailed analysis of the vehicle’s performance provides interesting insights into the challenges of autonomous urban driving systems. The paper concludes with a description of the events that led up to the collision with MIT’s Talus, and the resulting elimination of Caroline.

The paper, “The MIT–Cornell Collision and Why It Happened,” is an in-depth analysis into the collision between the MIT and the Cornell vehicles partway into the competition. This collaborative study, conducted jointly by MIT and Cornell, traces the sequence of events that preceded the collision and examines its root causes. A summary of robot–robot interactions during the race is presented. The logs from both vehicles are used to show the gulf between robot and human-driver behavior at close vehicle proximities. The paper ends with proposed approaches that could address the issues found to be at fault.

The paper, “A Perspective on Emerging Automotive Safety Applications, Derived from Lessons Learned through Participation in the DARPA Grand Challenges,” is a description of the entry led by Ford Motor Company. The article provides a motivation for robotics research as a means to achieve greater safety for passenger vehicles, with an analysis that suggests that human drivers are four to six times as competent as today’s autonomous vehicles. The article examines the design of the Ford team’s autonomous system and accompanying sensor suite. It presents a detailed analysis of vehicle performance during trials and the competition and concludes with lessons learned.

The final paper, “TerraMax: Team Oshkosh Urban Robot,” describes an entry
that was distinguished by its use of a 12-ton medium tactical vehicle replacement (MTVR), which provides the majority of the logistics support for the Marine Corps. Sensing was primarily done using passive computer vision augmented by laser scanning. The article provides a description of the system and an analysis of the performance during the competition, and during a run conducted afterward on the same course.

We hope that the papers collected here will be of interest to both roboticists and a wider audience of readers who are interested in learning about the state of the art in autonomous vehicle technology. The sensors, algorithms, and architectures described in these issues will no doubt soon be seen on highways, construction sites, and factory floors. Readers of this book might also be interested in a companion volume, The 2005 DARPA Grand Challenge: The Great Robot Race (Springer, 2007), which describes the technological innovation behind robots that raced in the 2005 DARPA Grand Challenge.

Finally, we would like to express our gratitude to the many individuals who served as reviewers of these papers, often through several iterations, and contributed to their high quality.

Martin Buehler
Karl Iagnemma
Sanjiv Singh
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Simmons, Reid
Spenko, Matthew
Stroupe, Ashley
Teller, Seth
Trepagnier, Paul
Vandapel, Nicolas
Urmson, Chris
Wang, Chieh-Chih (Bob)
Wooden, David
Yamauchi, Brian
Yoder, JD
Yoshida, Kazuya
Zlot, Robert
### Vehicle Name | Team Name | Result
---|---|---
Boss | Tartan Racing Team | Finished first in 250 minutes, 20 seconds.

Source: Tartan Racing Team
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junior</td>
<td>Stanford Racing Team</td>
<td>Finished second in 269 minutes, 28 seconds.</td>
</tr>
</tbody>
</table>

Source: DARPA
### Vehicle Name | Team Name | Result
---|---|---
Odin | Victor Tango | Finished third in 276 minutes, 38 seconds.

Source: Victor Tango
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talus</td>
<td>MIT</td>
<td>Finished fourth.</td>
</tr>
</tbody>
</table>

Source: DARPA
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Ben</td>
<td>Ben Franklin Racing Team</td>
<td>One of the six vehicles that finished the course (fifth or sixth place).</td>
</tr>
</tbody>
</table>

Source: DARPA
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skynet</td>
<td>Team Cornell</td>
<td>One of the six vehicles that finished the course (fifth or sixth place).</td>
</tr>
</tbody>
</table>

Source: DARPA
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>KnightRider</td>
<td>Team UCF</td>
<td>Drove for two hours until a GPS data failure occurred.</td>
</tr>
</tbody>
</table>

Source: DARPA
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>AnnieWay</td>
<td>Team AnnieWay</td>
<td>AnnieWay stopped due to a software exception that occurred while switching from road planning to zone navigation.</td>
</tr>
</tbody>
</table>

Source: DARPA
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caroline</td>
<td>CarOLO</td>
<td>Caroline drove 16.4 km (10.2 miles) and was retired shortly after a collision with MIT’s TALOS.</td>
</tr>
</tbody>
</table>

Source: DARPA
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>XAV-250</td>
<td>Intelligent Vehicle Systems</td>
<td>While waiting at a stop sign, a false positive (sensing a curb where there was none) together with a large time-out value caused an excessive wait which disqualified the vehicle.</td>
</tr>
</tbody>
</table>

Source: IVS
<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Team Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>TerraMax</td>
<td>Team Oshkosh</td>
<td>TerraMax completed the first four submissions in mission 1 before being stopped after a failure in the parking lot due to a software bug.</td>
</tr>
</tbody>
</table>

Source: Oshkosh
Contents

Autonomous Driving in Urban Environments: Boss and the Urban Challenge
Chris Urmson, Joshua Anhalt, Drew Bagnell, Christopher Baker, Robert Bittner, M.N. Clark, John Dolan, Dave Duggins, Tugrul Galatali, Chris Geyer, Michele Gittleman, Sam Harbaugh, Martial Hebert, Thomas M. Howard, Sascha Kolski, Alonzo Kelly, Maxim Likhachev, Matt McNaughton, Nick Miller, Kevin Peterson, Brian Pilnick, Raj Rajkumar, Paul Rybski, Bryan Salesky, Young-Woo Seo, Sanjiv Singh, Jarrod Snider, Anthony Stentz, William “Red” Whittaker, Ziv Wolkowicki, Jason Ziglar, Hong Bae, Thomas Brown, Daniel Demitrish, Bakhtiar Litkouhi, Jim Nickolaou, Varsha Sadekar, Wende Zhang, Joshua Struble, Michael Taylor, Michael Darms, Dave Ferguson ......................... 1

Motion Planning in Urban Environments
Dave Ferguson, Thomas M. Howard, Maxim Likhachev .......................... 61

Junior: The Stanford Entry in the Urban Challenge
Michael Montemerlo, Jan Becker, Suhrid Bhat, Hendrik Dahlkamp, Dmitri Dolgov, Scott Ettinger, Dirk Haehnel, Tim Hilden, Gabe Hoffmann, Burkhard Huhnke, Doug Johnston, Stefan Klumpp, Dirk Langer, Anthony Levandowski, Jesse Levinson, Julien Marcil, David Orenstein, Johannes Paefgen, Isaac Penny, Anna Petrovskaya, Mike Pflueger, Ganymed Stanek, David Stavens, Antone Vogt, Sebastian Thrun ................................. 91

Odin: Team VictorTango’s Entry in the DARPA Urban Challenge
Charles Reinholtz, Dennis Hong, Al Wicks, Andrew Bacha, Cheryl Bauman, Ruel Faruque, Michael Fleming, Chris Terwelp, Thomas Alberi, David Anderson, Stephen Cacciola, Patrick Currier, Aaron Dalton, Jesse Farmer, Jesse Hurdus, Shaun Kimmel, Peter King, Andrew Taylor, David Van Covern, Mike Webster........ 125
A Perception-Driven Autonomous Urban Vehicle

Little Ben: The Ben Franklin Racing Team’s Entry in the 2007 DARPA Urban Challenge
Jon Bohren, Tully Foote, Jim Keller, Alex Kushleyev, Daniel Lee, Alex Stewart, Paul Vernaza, Jason Derenick, John Spletzer, Brian Satterfield ................................................................. 231

Team Cornell’s Skynet: Robust Perception and Planning in an Urban Environment
Isaac Miller, Mark Campbell, Dan Huttenlocher, Aaron Nathan, Frank-Robert Kline, Pete Moran, Noah Zych, Brian Schimpf, Sergei Lupashin, Ephrahim Garcia, Jason Catlin, Mike Kurdziel, Hikaru Fujishima .......................................................... 257

A Practical Approach to Robotic Design for the DARPA Urban Challenge
Benjamin J. Patz, Yiannis Papelis, Remo Pillat, Gary Stein, Don Harper ................................................................. 305

Team AnnieWAY’s Autonomous System for the DARPA Urban Challenge 2007
Sören Kammel, Julius Ziegler, Benjamin Pitzer, Moritz Werling, Tobias Gindele, Daniel Jagzent, Joachim Schöder, Michael Thuy, Matthias Goebel, Felix von Hundlehause, Oliver Pink, Christian Frese, Christoph Stiller ........................................ 359

Driving with Tentacles - Integral Structures for Sensing and Motion
Caroline: An Autonomously Driving Vehicle for Urban Environments

The MIT – Cornell Collision and Why It Happened
Luke Fletcher, Seth Teller, Edwin Olson, David Moore, Yoshiaki Kuwata, Jonathan How, John Leonard, Isaac Miller, Mark Campbell, Dan Huttenlocher, Aaron Nathan, Frank-Robert Kline ................................................................. 509

A Perspective on Emerging Automotive Safety Applications, Derived from Lessons Learned through Participation in the DARPA Grand Challenges

TerraMax: Team Oshkosh Urban Robot
Yi-Liang Chen, Venkataraman Sundareswaran, Craig Anderson, Alberto Broggi, Paolo Grisleri, Pier Paolo Porta, Paolo Zani, John Beck .......................................................... 595

Author Index ................................................................. 623