

Advancing Robotics: The Urban Challenge Effect

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The Defense Advanced Research Project Agency's (DARPA) Urban Challenge, a contest that pitted robots against each other for 6 h without human intervention, was aimed at advancing the state-of-the-art in research for perception, planning, sensors, and situational awareness with the goal of military application. The event was a success, gaining national media attention for DARPA and robotics; but how well did DARPA succeed in advancing research for the military? To answer this question, a number of post-event activities conducted by Lockheed Martin Advanced Technology Laboratories, a participating member of the Ben Franklin Racing Team, will be presented and examined. In addition, a comparison of requirements between the Urban Challenge contest and current military applications will be conducted.

I. Introduction

IT is rare to be both a part of history and to write it. That is what we attempt to accomplish at the Defense Advanced Research Project Agency (DARPA) Urban Challenge. This paper pulls ourselves back for a moment and tries to view the field from afar, seeing from whence we have come and anticipating where we will go. DARPA's Grand Challenges have become a large part of robotic history. At the same time, there is a congressional mandate that sets a goal for the future that a third of all ground vehicles in the military be robotic. How far have we come and how far do we have yet to go? Answering these questions is the focus of this material.

The Urban Challenge (Fig. 1) was DARPA's third Grand Challenge—a contest that pitted robotic vehicles against each other in a simulated urban environment. The final event included 11 robotic vehicles and their DARPA chase cars, along with 50 manned vehicles that were used to simulate various traffic situations. All robotics vehicles were required to be completely autonomous and team members were not allowed on the course while the vehicles were running. The contest was both a race, with a maximum time limit of 6 h, and a “driver's test” for the autonomous vehicles that evaluated their skill in executing maneuvers that a typical human driver would encounter on populated city streets.

For brevity, we will not list all the requirements for the Urban Challenge. In summary, the Urban Challenge required vehicles to detect roads, lanes, and other vehicles; perform left, right, and U turns; pull in and out of parking spaces; merge into traffic; change lanes in traffic; queue up in line at traffic stops; understand and follow intersection precedence; and avoid collisions at all times [1,2]. In general, DARPA required all vehicles to obey California driving laws and be safe at all times while performing missions over a 60 mile course in under 6 h [3].

This set of requirements was vastly different from previous Grand Challenges, and arguably more challenging, owing to the focus on interaction with other vehicles. Previous installments in the Grand Challenge were primarily

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Fig. 1 DARPA’s Urban Challenge was the third installment in the Grand Challenge series.

focused on negotiating difficult terrain while moving between two points. These requirements fit in well with DARPA’s stated goal of producing vehicles that could perform automated supply missions.

The Ben Franklin Racing Team was a consortium led by the University of Pennsylvania with Lehigh University and Lockheed Martin Advanced Technology Laboratories (LM ATL). Based in the Philadelphia area, the team consisted of a dozen engineers who worked on the project for 18 months [4].

To design a vehicle that could fulfill these requirements within our limited budget (no DARPA funding) and compressed schedule, our team took a surprisingly simple approach. We identified a number of the key requirements for perception and interaction that would define the maximum capabilities of our system and created a series of “worst case” vignettes that could be used to design test cases for our systems [5]. These test cases, initially occupying the realm of paper and viewgraphs and used as thought experiments in design and analysis, would eventually be turned into a set of test scenarios for a live system with associated pass and fail criteria. These test scenarios were executed under a variety of conditions (Fig. 2).

Our team took the approach of creating a system that would complete the course, first and foremost, while remaining cautious and safe to the greatest extent possible without sacrificing our main goal. In our design, persistence, elegance,

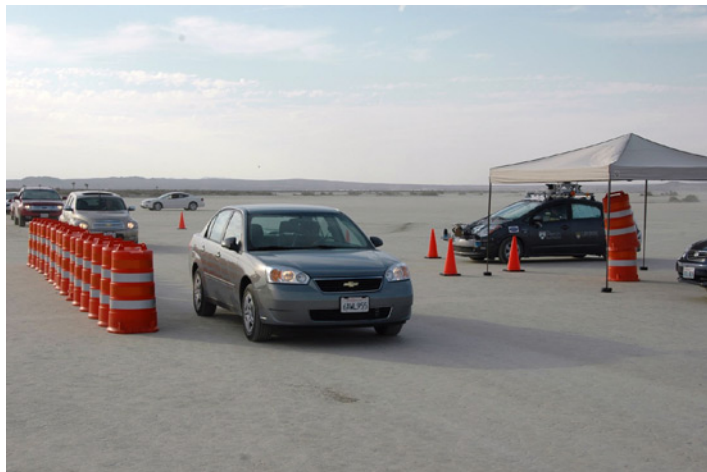


Fig. 2 The Ben Franklin Racing Team performing testing at a dry lake bed near the site of the Urban Challenge Final Event.



Fig. 3 “Little Ben” crossing the finish line of the Urban Challenge after six hours of autonomous operation.

and agility were valued over speed and aggressiveness. This affected all factors of our system from platform choice to software architecture and, in the end, served us well.

The Ben Franklin Racing Team was dramatically handicapped in a field of competitors who had the benefit of participating in previous DARPA challenges, had established sponsors, regularly spent millions per year on their effort, and had been awarded seed money from DARPA to pursue the Urban Challenge. Despite these deficits, the team lived up to its dark horse spirit, performing flawlessly at DARPA’s site visit, being among the first teams selected at the National Qualification Event as a finalist, and being one of only six teams to complete the race (Fig. 3).

With the benefit of time passing, the critical decisions that clearly contributed to the success of the team resolve more sharply into focus. In short, these were the acquisition of the Velodyne LIDAR, the commitment to system testing in varied environments, the simplicity and adjustability of the software architecture, and the overall flexibility of the design.

II. Lockheed Martin’s Urban Challenge Vehicle

To ensure that a catastrophic loss of our vehicle would not dash the efforts of our team competing in the challenge, an identical vehicle was purchased by Lockheed Martin and outfitted with essential electronics so that, in an emergency, sensor and computing hardware could be quickly transferred with minimal impact to the system. Fortunately, this contingency plan was not required and the primary vehicle completed the challenge without incurring any damage.

In the months following the Urban Challenge, Lockheed Martin, using the former backup vehicle, invested time and material into creating a system that was similar in many ways to the vehicle that competed in DARPA’s contest. The commercial platform, a 2006 Toyota Prius, was identical, as was the AEVIT drive-by-wire system, electronic stop hardware, and network infrastructure. However, the sensor and computing packages were greatly reduced in complexity. This was attributable in part to budgetary constraints but was largely driven by the “hunch” that it might be possible to create a system with less complexity while retaining a large amount of capability. To this end, the sensors were limited to a global positioning system (GPS)/inertial measurement unit (IMU) for position, a Velodyne LIDAR for perception, and a single laptop for processing. In contrast, the vehicle that competed in the Urban Challenge used 11 sensors and five, dual-core processors (Fig. 4).

The software architecture largely remained intact with a single layer of processing replaced at the “mission” level that allowed us to incorporate some of Lockheed Martin’s research products for further development and evaluation. These research products include the Metis software framework and the role-based operations (RBO) software system, which is built using Metis. Metis is an agent-based framework for robotic control that is based on the belief, desire, and intention (BDI) model of human reasoning. RBO is a teaming technology that allows humans and robots effectively to coordinate by routing tasks and information using team roles. Both of these systems have been transitioned to

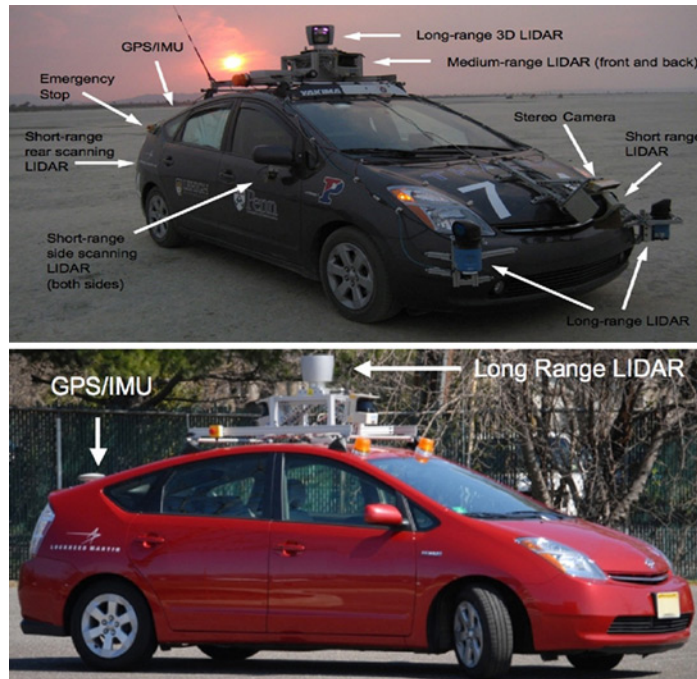


Fig. 4 Using an identical platform, the backup vehicle dispensed with the majority of sensors used by “Little Ben” and relies upon the Velodyne LIDAR system.

Lockheed Martin Missiles and Fire Control, a division within Lockheed Martin that supports unmanned ground vehicle (UGV) development for the Department of Defense (DoD).

A. Activities Since Urban Challenge

1. Fort Benning Experimentation

The system described above was taken to Fort Benning, Georgia, home of the U.S. Army Infantry School, in March 2008 to evaluate the technology in a military environment. A set of missions, similar to those used in the Urban Challenge, were created using the road network and the Military Operations on Urban Terrain (MOUT) site that was located on base (Fig. 5). The major differences between this experiment and the Urban Challenge were the terrain, which was considerably more hostile, and the urban area, which was cramped by comparison. The experiment was conducted to evaluate a number of issues relating to the robustness and generality of the system, having not been tuned to the specific location before to the experiment. The system performed successfully in areas that were previously unknown to it with only minor issues that could be overcome with a more capable platform (Fig. 6).

Specifically, the issues encountered were as outlined below.

- 1) *A transition from road surface to grass in locations where GPS was extremely poor.* This occurred a number of times but lasted only a few seconds and was corrected automatically.
- 2) *Lack of detection of negative obstacles close to the vehicle whilst performing a K-turn.* This occurred once, while performing a K-turn on a gravel section of road that tapered off dramatically into the forest area. The system was E-stopped and manually driven clear of the road segment.
- 3) *Near collision with a short wall (approximately 1 ft in height).* This occurred once while turning into the MOUT site. The system was E-stopped and manually driven around the wall. The system successfully navigated the same location during a later portion of the experiment.

In contrast there were many surprising successes of the system, which included:

- 1) The ability of the system to continually perform well with a single sensor for perception and a single laptop for processing.



Fig. 5 A map of Fort Benning shows, in orange, the route network used by the autonomous vehicle.

- 2) The ability of the system to autonomously navigate through relatively poor terrain. The terrain encountered in the Urban Challenge largely consisted of urban streets with clear delineations between road surface and off-road areas, which was not the case at Fort Benning.
- 3) The overall robustness of the system. During the three-day experiment, the system was E-stopped only a handful of times and did not encounter a single software or hardware failure.

Overall the system performed extraordinarily well over the three-day experiment. Our conclusion was that all of the minor failures of the system could be overcome with a more terrain-capable platform, which would negate the effect that terrain had on the low-profile Prius.

2. Toyota Grand Prix

In April 2008, Lockheed Martin participated in a demonstration of robotic technology at the 34th Annual Toyota Grand Prix of Long Beach (Fig. 7) along with Carnegie Mellon University and Stanford University. The objective was to demonstrate that a robotic vehicle could autonomously navigate a racetrack at speeds up to 30 mph.

Because this event was a very public event with national media coverage, arguably more than the Urban Challenge, the approach of all three teams was to keep it simple and low-risk by removing any competitive element by adopting a 30 mph speed restriction, staged vehicle launches that were 2 min apart and the agreement that vehicle passing would be disabled to ensure that no vehicle collisions would occur.

To prepare for the demonstration, GPS points and LIDAR data were gathered ahead of the event and teams were allowed approximately 4 h for practice runs at night while the course was closed. It was necessary to hold practice



Fig. 6 All of the issues encountered at Fort Benning could be mitigated with an off-road platform.



Fig. 7 The Toyota Grand Prix of Long Beach is the longest running event of its kind.



Fig. 8 The Grand Prix course is made up of city streets and winds through numerous large office buildings, hotels, and parking structures.

runs at this time as the course used roads that were populated by the public during the day, segments of which went against the normal flow of traffic, and needed to be closed and monitored by city police (Fig. 8).

During practice runs an issue was discovered regarding the GPS signal. The backside of the course passed under two wide, thick concrete footbridges that were flanked by large hotels on the left and a parking garage on the right, creating an environment of total GPS loss for approximately 600 ft. The resulting behavior of our system when it entered this area was to quickly reduce speed and “wander” from left to right attempting to reacquire its bearings. To overcome this effect, we implemented a wall-following algorithm, which performed well given the thick concrete walls surrounding the track, reducing the visible indecision of the system during GPS outages.

As mentioned earlier, the approach used for the Urban Challenge was primarily focused on safety and completing the course. Owing to this focus, the system had not been previously tested extensively at higher speeds approaching the 30 mph that was required for the Grand Prix demonstration. This was an area that was of greater focus in our preparation for the Grand Prix.

During the demonstration the system performed well, hesitating briefly during the period of GPS outage and running the remainder of the course smoothly at speeds up to 30 mph (Fig. 9).



Fig. 9 Participating in the Toyota Grand Prix was an opportunity to see how well our system could adapt to new environments.

III. Military Applications

A. DoD Unmanned Ground Vehicle Program Summary

The majority of UGVs in the DoD are currently being designed and tested under the Army's Future Combat Systems (FCS) program. FCS has identified a number of ground platforms for use by the future army, three of which are currently programs of record: the Soldier Unmanned Ground Vehicle (SUGV), the Multifunction Utility/Logistics Equipment Vehicle (MULE), and the Armed Reconnaissance Vehicle (ARV) (Fig. 10).

B. Requirements

The DoD has specified requirements for only a few unmanned vehicles. In fact, the FCS line of vehicles is the only set of ground vehicles that have a formally defined set of requirements. The majority of these definitions deal with the robustness of the vehicle under operational stress. However, there are few defined requirements for autonomy related functions. To begin evaluating autonomous systems for their ability to meet future military needs, we start with the Urban Challenge requirements and then look beyond to the conditions vehicles will encounter in battlefield environments. To begin to understand these differences one must understand the environment in which these vehicles will operate:

- 1) in complex and hostile terrain
- 2) at all times of day and night
- 3) in GPS-denied areas
- 4) in extreme weather conditions
- 5) among military personnel
- 6) among other vehicles

At a glance, it is easy to see that the requirements of the Urban Challenge were clearly centered on the ability of the vehicle to interact with other vehicles. In fact, DARPA stated this in the Urban Challenge Rules:

"In the National Defense Authorization Act for Fiscal Year 2001, Congress mandated in Section 220 that "It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that . . . by 2015, one-third of the operational ground combat vehicles are unmanned." With the Urban Challenge, DARPA is focused on the advancement of technology to address the operational challenges implicit in the Congressional mandate. Safe and effective operation in moving traffic is a basic requirement for all future military missions for ground autonomous vehicles." [1]

Obviously, the requirements for an operational military unmanned vehicle are much greater than what was required to succeed in DARPA's Urban Challenge. However, Lockheed Martin has created a vehicle to address these additional requirements called the Squad Mission Support System (SMSS).

C. SMSS UGV Description

The SMSS UGV is a six-wheeled, diesel-powered, all-terrain vehicle currently in development by Lockheed Martin's Missiles and Fire Control division [6]. With a payload capacity of 1000 pounds, the SMSS is designed to support a single squad over varied terrain. A powerful suite of sensing technologies is used to allow this already highly



Fig. 10 The SUGV, MULE, and ARV are the ground vehicles defined by the Army's Future Combat Systems program.

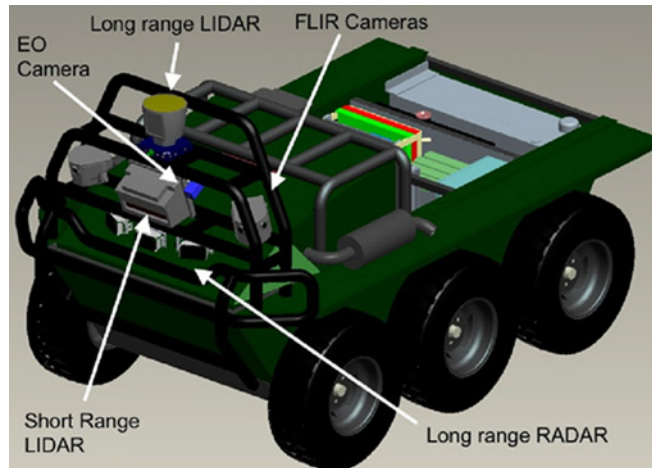


Fig. 11 The sensor configuration for the Squad Mission Support System was guided by our Urban Challenge experiences.

capable vehicle of autonomous traversal of varied and difficult terrain. The SMSS also has amphibious capabilities that allow it to ford rivers and streams (Fig. 11).

The SMSS's size is similar to that of the Toyota Prius used during the Urban Challenge events. It presents a much more capable vehicle that can easily integrate with the technologies developed before and after the DARPA Urban Challenge. The SMSS's track-steering presents interesting challenges and also creates the potential for much tighter vehicle control. The ability to turn in place would allow the SMSS to go down streets and alleyways that would be troublesome to front-wheel steering vehicles.

D. Transition of Urban Challenge Technology

One of the goals of Lockheed Martin Advanced Technology Laboratories is to work with academic researchers and other partners to develop advanced technology that can be hardened, tested in a setting that is operationally relevant, and used to develop technology prototypes that can be transitioned to other segments of Lockheed Martin. The Urban Challenge project was a perfect model for this type of transition. Before the project we had identified a number of operating divisions that were interested in autonomy for tactical unmanned vehicles, and with the success we enjoyed at the final event, we have begun the effort to transition the technology to their respective products.

Lockheed Martin Missiles and Fire Control division was interested in the autonomous navigation system for the SMSS and commissioned LM ATL to demonstrate the technology at Fort Benning. This successful demonstration led to a request for the system to be installed onto the SMSS vehicle. Following this demonstration, we successfully installed and tested the Urban Challenge software suite on the SMSS within three days, a testament to the wide applicability of the system.

E. Discussion of Gaps

Two important areas must be addressed before a UGV can be integrated into the DoD services as an autonomous unit: trust and mission-level behaviors. We will describe these issues and show how they are related and dependent on each other.

The issue of trust goes to the fundamental ability for a warfighter to believe that the UGV will behave in such a way that provides confidence to the warfighting team. Essentially, this means performing in a predictable and safe manner. During the first two DARPA challenges, it was clear that trust was low concerning the abilities of the robotic vehicles because of the lack of interaction with other vehicles and the secluded nature of the test. However, this changed during the Urban Challenge, where humans interacted with the robotic cars and, under the closed circuit

course, there was a level of “trust” between the 50 human drivers and the Urban Challenge finalist vehicles. This level of trust was achieved through three key elements of the Urban Challenge process:

- 1) a well-defined set of requirements for the autonomous vehicles, with strong emphasis on safety;
- 2) a set of successively more challenging trials, ranging from a video demonstration to the grueling tests of the National Qualifying Event, to weed out vehicles that were not capable or which demonstrated unsafe or unpredictable behavior;
- 3) continued availability, through the Final Event, of the Emergency Stop (E-Stop) system on all autonomous vehicles, which allowed the human participants to take control of vehicles in emergency situations.

Through the application of these measures over the 18 months of the Urban Challenge process, a considerable measure of trust was gained in the 11 vehicles selected for the final event. This trust was rewarded by the fact that no collisions occurred between unmanned vehicles and any of the 50 manned vehicles on the course. Regardless, most human drivers today would not trust those same vehicles to operate on public roads in normal traffic, and most warfighters would likewise have very limited trust in a poorly structured battlefield environment. This points to a confidence issue between unmanned vehicles and humans in the environment.

To advance unmanned vehicle acceptance and trust in the military and the commercial sector they must be introduced into relevant environments with constant testing and improvement, and they must be shown to be able to do more than “simple” tasks such as point to point navigation. It is critical to define a set of “mission level” baseline behaviors that are useful, understandable, and reliable. If a set of tasks, executed by an unmanned system, could be encapsulated into a single mission level behavior that is well understood by humans with regard to expected results and could be made reliable from a technology standpoint, then the beginnings of a trusted system would emerge.

The Urban Challenge provided for a first level cut at the usage of mission-level behaviors for onroad operations in city type environments. The rules of the road, common courtesies, and “timeout” operations could all be encoded into the vehicles. This needs to be expanded to include traffic signs, stoplights, and more complicated urban terrain. Experiments such as the Urban Challenge should continue so that both the military and the general public obtain a better understanding of the technology and where it is heading.

IV. Future Work

A. Beyond the Gaps

Dealing with diverse environmental conditions and pedestrians operating around vehicles are two problems that were not addressed in the DARPA Grand Challenges. In addition, unmanned systems must perform various types of missions from support missions to reconnaissance, calling upon a number of behaviors to complete those missions. This level of competency and breadth of applicability is no small feat.

For autonomous vehicles to be relevant to military operations, they will have to operate at any time of day and in any weather. A combination of the sensors used in the Grand Challenges may be able to achieve this, but no systematic effort has been made to verify and validate this approach.

Military vehicles operate around other people. Whether operating around warfighters, civilians, or enemies, autonomous vehicles used for military purposes must comply with safety requirements. In addition to having algorithms that ensure the vehicle performs safely, autonomous vehicles will have to be trusted by the warfighters using them. Extensive research must be done on sensors and algorithms that can be used to sense and anticipate human actions without false negatives in any environmental condition.

B. Sensor Limitations

The Urban Challenge system depended heavily on the Velodyne 3-d LADAR sensor for perception and obstacle avoidance. The Velodyne HDL-64E provides more information in a single sensor than was previously obtainable from multiple sensors (Fig. 12). While it is a very impressive sensor and ranks among the best available off-the-shelf sensors, there are certainly limitations that leave room for improvement. The sensor is not capable of detecting objects close in to the vehicle, which leaves a large cone-shaped blind spot that must be filled by other sensors. Without additional sensing, curbs and small obstacles must be detected before the vehicle entering the sensor’s limit zone. In the Urban Challenge event, this shortcoming was overcome by the use of close-range sensors specifically targeted at this type of detection.

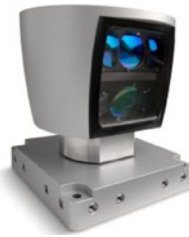


Fig. 12 The Velodyne HDL-64E emerged as a critical sensor at the Urban Challenge.

In addition, the sensing range is not long enough for high-speed applications. As vehicle speed increases, the distance requirement for the initial detection of an obstacle also increases because planning obstacle avoidance and performing maneuvers is a constant. The maximum range of the Velodyne is 120 m, but at this distance only very large obstacles can be detected due to the small number of laser returns per square foot. The effective range of the sensor is around 50 m, where nearly every object that a vehicle would be required to avoid can be detected.

As impressive as the Velodyne is, substantial work is required to provide more resolution at greater ranges. In addition, to detect objects that are extremely close to the vehicle additional sensors will be required.

C. UGVs Outperforming Human Drivers

According to DARPA the four of the six (including “Little Ben”) finishers of the Urban Challenge would have passed the State of California Driver’s Exam. Despite this, there is still a long way to go before unmanned vehicles outperform human drivers. Humans are able to classify and react to numerous situations and reason about what to do in more complicated cases. For the near future, UGVs will be useful to humans because they can perform tasks that humans do not wish to do, not because they can do them better.

For UGVs to perform better than humans, they will need to have expectations about the environment—expectations that are realistic and reasonably accurate without being given much information. To accomplish this, an unmanned system will need to pull from multiple models of the environment and models of behavior for teammates and enemies; integrate models of the activity that it is performing; interpolate and extrapolate between the information it perceives and the information it expects; and perform all these tasks in near real time.

Integration of autonomous vehicles into military operations will require vehicles that can perform tactically relevant military behaviors. These involve mission-specific activities in addition to navigating from one point to another. For example, in a cordon and search operation vehicles may be expected to form a perimeter around an area and prevent non-military personnel from exiting the area. These behaviors are different than what would be required to execute a convoy scenario or a medical evacuation. Developing a system that can identify the correct behavior to use, adapt it to the current mission, and adapt it further to a changing environment will be extremely difficult and is one of the hard problems that the field of robotics now faces.

V. Conclusions

A. Advancing Robotics Through Urban Challenge

As we have seen, the Urban Challenge has advanced robotics in the areas of autonomy and coordination with other vehicles in an urban setting. However, there are two ways in which robotics have been advanced that are of high importance to military operations: generality and robustness. It would appear that systems that could perform autonomously in unknown and fairly complex environments for periods of 6 h or more would do well in other, unknown environments. The assumption is that in achieving a system that can complete the Urban Challenge, one has imbued that system with logic that is applicable to many environments and with a level of robustness that allows for a large mean time between failures. The extent to which this was accomplished can be seen through some of the experiments and demonstrations in which Lockheed Martin has applied the technology developed through its pursuit of the Urban Challenge, specifically our experiments at Fort Benning.

Given this, the fact that DARPA withheld the location of the final event—forcing competitors to create systems that could perform in any environment—and the fact that the length of the race was 6 h—which required teams to

Table 1 The requirements for military operation are extreme and have been addressed in part by DARPA's Grand Challenges

Capability	DARPA event
Complex and hostile terrain	DARPA Grand Challenges I & II
Operate among other vehicles	DARPA Urban Challenge
Extreme conditions (night, weather, etc.)	Not handled
Operate in extended GPS-denied areas	Not handled
Operate among military personnel	Not handled

create systems that were robust—were at least as much, if not more, important in terms of advancing robotics for the military than any of the other requirements.

In the final analysis, DARPA's Urban Challenge has advanced robotics in many ways with a sometimes surprising source for that advancement. The robotic systems participating in the final event exhibited intelligent behavior in the face of complex situations throughout the six-hour contest. In fact, announcers and onlookers were often heard anthropomorphizing the systems, calling them "cautious," "aggressive," "smart," and so on. In the authors' opinion, this was one of the greatest rewards in creating such a system.

B. Accomplishing the Goals of Urban Challenge

How well did DARPA do in achieving their goals of creating robotic systems that can perform "safe and effective operation in moving traffic" to "address the operational challenges implicit in the Congressional mandate?"

Of the six finishers, four passed their "driver's test" without causing or being involved in a collision. In fact, in the final event there was only one robot-to-robot collision and no robot-to-human collisions, a testament to the safety of these systems. In addition, in all of the post-challenge activities LM ATL has participated in, our autonomous system has not caused or been involved in a single collision.

In terms of effectiveness, the missions used in Urban Challenge were modeled after supply sustainment routes. The finishers all performed these missions well and our system has performed well conducting other missions detailed in this paper. Exactly how effective these systems would be performing real-world military missions is a question that requires further work to answer. In the not-too-distant future, Lockheed Martin will demonstrate a system that will finally answer this question.

C. Further Work

As much as robotics may have been advanced through the Urban Challenge, many aspects in the broad military interests have not been addressed (Table 1).

It is probably the case that the operation of an unmanned vehicle in extreme conditions is "mostly engineering" and does not require "new innovations;" however, this is not true with operation in and around groups of personnel or in GPS-denied areas. To accomplish this, new ways of perceiving and tracking objects will be required. In addition, a fundamental change in how planning is performed will be needed to overcome the high degree of uncertainty and computational difficulty of interacting with high numbers of independently moving objects. Finally, deployed systems will need to perform successful navigation with only relative location and a rough estimate of global position.

Although no future grand challenges are planned, some of the aspects above may still be addressed through DARPA programs or other research agencies, possibly even through independent academic or industry research. What is certain is that they will be solved, one way or another, by the robotics research community and when that day comes the U.S. military and the general population will greatly benefit.

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