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BUILDING THE TECHNOLOGIES FOR THE MINE SITES OF THE FUTURE

THE TIME IS RIGHT FOR AUTONOMY

Many mining companies consider autonomy the key to the future of their industry—and for good reason. A successful autonomous mining haulage system accomplishes a number of their key goals, including positively impacting safety and increasing productivity.

The development of autonomous mining has been a topic in the industry for more than a decade. Caterpillar first demonstrated the technology at MINExpo in 1996, but found not only that the technology was not ready at that time—but its customers weren't ready either.

"Mines didn't have the same business drivers then that they do now," says Caterpillar's Ed McCord, product manager, large mining trucks. "When we talked with the customers about what they needed, they indicated they weren't ready for autonomy."

Mike Verheyen, Caterpillar Electronics & Connected Worksite product manager, recalls, "Based on what the mines told us and the limited technology at the time, we focused on addressing their immediate needs, while continuing our autonomy program behind the scenes—concentrating on the building blocks that are becoming the autonomous system of the future."

THE TIME IS NOW

As technology improved and mining companies faced new challenges in people and productivity, autonomy again came to the forefront of the industry and the equipment manufacturers who support it. But perhaps the main driver for the autonomy push is the boom in the mining industry.

Commodity prices are strong and economies are thriving—and the demand for minerals has grown at a staggering rate. Mining companies eager to take advantage of the situation are working to quickly move as much material as they possibly can—while maintaining their focus on safety.

"In the previous decades, mining companies were meeting the demand with the equipment and the people that they had," says Ken Edwards, Caterpillar mining technology manager. "That's not true today. In order for them to capitalize on the demand, they need to get more ore out of the ground as quickly and efficiently as possible."

In addition, the mining boom has led to a time of profitability for mining companies—and the funds they need to invest in the future. "Mining companies now have the money for research and development, and they are focused on autonomy as one of the technologies they want to see move forward to support their operations," says Edwards.

THE BENEFITS OF AUTONOMY

Mining companies look at autonomy as an enabler that will help them make quantum leaps in safety, efficiency and productivity—lowering costs and increasing availability.

Safety

"Zero injuries is the mantra of mining companies," says McCord. "A switch to autonomous mining equipment will have a tremendous influence on their achievement of that goal. When you can remove the operator from harm's way, he is not impacted by any of these concerns."

For example, significant injuries can occur as operators access or egress from a machine. However, with an autonomous machine, there is significantly less need for a person to climb on and off.

Studies have also shown that head-to-head and head-to-tail truck crashes are some of the most common collisions in a mine. With autonomy, the interaction between machines is tightly controlled with various layers of redundancy to prevent non-manned vehicles from hitting each other.

Consistency of operations

A key benefit of autonomous mining is consistency of operations. All workers feel fatigue at the end of the day—whether they're working in a truck or in a mine office. As a result, their efficiency goes down. "Inefficiencies and human inconsistencies can add up to millions of dollars of operating expenses or lost revenue," says Edwards. Consistency leads to better efficiencies, lower costs and higher overall productivity.

Autonomous mining allows for repeatability and consistency by using software to manage the processs. Consistency results in a number of potential benefits:

- In an autonomous operation, a truck can be programmed to consistently back under the shovel to within 25 centimeters (10 inches) all day, every day—so the shovel operator does not have to waste valuable time trying to chase the truck due to poor spotting.
- An autonomous truck cycle time will be consistent throughout the shift—beginning, end, and in the middle.
- An operator gets tired at the end of a shift, while an autonomous machine operates at the same efficiency 24/7.
- Visual truck safety checks can be done during fueling, while the truck's health is being continually monitored by on-board health monitoring systems such as VIMS (Vital Information Management System).
- An autonomous system will eliminate misdirected loads.
- With "virtual shift change" on the trucks, bunching at the start and end of the shift will significantly disappear.
- By controlling speed, location, and truck routes, the autonomous system may offer improved algorithms to impact tire life.
- Consistently running the truck within design specifications improves mechanical availability.
- Allowing the on-board and off-board computers to maximize the truck and the autonomous system may provide opportunities to minimize fuel burned during the load-haul-dump cycle. Caterpillar's autonomous mine and truck simulator will be used for testing fuel efficiency.

"With an autonomous system, the truck will do whatever the shift supervisors have told the software to do—and it will do it consistently," says McCord. "This will improve efficiency and utilization and result in a lower cost-per-ton—the goal of every mining company."

Time wasted due to inconsistencies and inefficiencies adds up to millions of dollars of operating expenses, Edwards explains. "Mines want to work to their maximum potential at all times. This is the key role that autonomous machines and mining technology products play in the future of mining."

People shortage

As mine sites move into more remote areas, it becomes even more difficult to find qualified people willing to operate the equipment. And the increase in mining activity worldwide has depleted the existing pool of operators. Autonomous equipment offers a solution to this issue.

"Mining companies want to expand their operations and increase production to take advantage of the boom, and they just can't get the people," says Edwards. By making new or expanded sites autonomous, current employees can be deployed to other positions while autonomy makes up the gap.

"Mines will always need people, so it's not a matter of companies reducing their work force," says McCord. "Rather, they will be able to increase production using the employees they already have."

Autonomy also may play a role in attracting a new generation of employees to work in mines. "This generation has grown up with high-powered computers, instant communication and the Internet," says Michael Murphy, autonomous mining commercial manager. "Autonomy's 'video game' feel is something that will attract them to work in the industry. It will be something they easily accept."

In addition, autonomous mining will allow mining companies to reduce the infrastructure required for operations. When fewer people are working on-site, there is less housing to build, less training required, and fewer flights to and from remote areas.

THE TECHNOLOGY BUILDING BLOCKS

Over the past 10 years, Caterpillar has focused on building the core technologies for autonomy, understanding that they would be needed one day. In fact, mining companies around the world are using the building blocks of autonomous technology on surface and underground sites every day.

Today's technologies include:

- Autonomous equipment systems such as MINEGEM, which is used in a number of underground mines.
- Information management systems
- Machine health and condition monitoring systems
- High-precision Global Positioning System (GPS)-based guidance and control systems
- Broadband wireless communication technologies

"Caterpillar has continued to advance toward autonomy over the past 10 years by focusing on the key core technologies and products, which we call building blocks," says Verheyen. "The advancement of our fleet management system, onboard monitoring systems and research on cost-effective radar are examples of work directly linked to autonomous systems."

Cat customers use a number of products that are considered the building blocks of autonomy: MineStar™ Fleet Commander, MineStar™ Health, MINEGEM, AQUILA™ Drill and Dragline Systems, VIMS, Computer Aided Earthmoving System (CAES), Slow Speed Object Detection, Remote Control, Condition Monitoring, and Predictive Analysis Service.

"Today's technology is laying the foundation for a technology revolution that will change the face of the mining industry for years to come," says Chris Curfman, president of Caterpillar's Global Mining Division. The technology is moving from machine guidance systems, to integrated automated machine controls, to remote control operations, to autonomous machines, and finally to autonomous mine sites.

TECHNOLOGY PARTNERSHIPS

Leading universities have partnered with equipment manufacturers to begin enhancing the core technologies for a fully integrated, autonomous mine site. One such partnership exists between Caterpillar and Carnegie Mellon, a global research university of more than 10,000 students, 70,000 alumni and 4,000 faculty and staff.

"We're aligning ourselves with the best and the brightest minds in the fields of science and engineering," says Gwenne Henricks, Caterpillar vice president of Electronics and Connected Worksite.

The Caterpillar / Carnegie Mellon collaboration is a longstanding relationship, created to co-develop automated equipment.

"I've been working with Caterpillar for more than 20 years," says robotics professor William "Red" Whittaker. "And one of the outcomes of our partnership has been 13 patents for technologies and inventions."

The two organizations are co-inventors of GPS guidance for off-road machines, computer planning for robotic digging, and operator-assistance for loading trucks.

"The utilization of GPS to guide an outdoor vehicle was envisioned and created 20 years ago—before the GPS constellation was even in the sky," Whittaker recalls. "No one else could even envision that it would be a core technology used across all types of outdoor machines."

The collaboration also resulted in the development of sensors to safeguard a moving vehicle. "It's essential that a vehicle sees where it's going and stays out of trouble," Whittaker says. "Equipment operators are able to sense their surroundings, make plans, and then take action. Humans aren't even conscious of the fact that we are sensing, feeling, hearing and seeing. We just do it. But machines need technologies to help them see and react to what's around them."

For example, if a machine needs to follow a haul road that requires a right turn, it must be told first to see the road. Then it must plan to make a turn; operate the steering, braking and throttle in order to take that action; then decelerate into the turn and accelerate when coming out of the turn.

Caterpillar and the university also have developed technologies that make it possible to orchestrate multiple vehicles on a mine site—which requires fleets of machines to do the digging, the loading and the hauling.

Typical projects begin as two-year studies at the university. Once the technologies have reached a level of relevance and their viability for a product appears solid, then the organizations work together to create a prototype of the product or feature on a Cat machine. In addition to Caterpillar, Carnegie Mellon has a number of other research partners in industries like automotive, defense and agriculture. That ongoing research—which leads to technological advances—also becomes valuable in the projects CMU is developing with Cat.

The collaboration strengthens the knowledge base of both organizations. It exposes both CMU and Caterpillar researchers to the rigors of applied science and engineering, and to leading-edge automation challenges.

ADVANCEMENTS IN TECHNOLOGY

While the technology was not viable when Caterpillar was ready to introduce autonomy more than a decade ago, that is no longer the case. "Technology has moved forward by leaps and bounds in the last 15 years," says Verheyen. "Back when Cat first demonstrated its autonomous truck, the Internet was in its infancy and WiFi-radio communication was a concept in the university research labs. And it was like something out of 'Star Wars' to think that you could get your e-mail anywhere in the world on a hand-held device."

CMU's Whittaker agrees, explaining how far technology has come since the university began collaborating with Caterpillar more than 20 years ago. "When the technological advances are viewed over decades, it's almost like going from fantasy and science fiction to reality and manifestation," he says. "The differences are profound."

"Every version of what we develop builds in aspects of technologies we've developed before," he continues. "It benefits from advances we create together—and the advances the world creates for us."

Automation technology has benefited from advances in computing, in GPS, in gyroscopes and many others, says Whittaker. "The mining industry and Cat and Carnegie Mellon didn't directly improve those things," he says. "But mine automation benefits immensely from them."

GPS

The GPS constellations that are so important for autonomous navigation did not even exist 15 years ago, recalls Whittaker. "In 1990 it took several racks of electronics and processors just to estimate the machine's position—and even then we couldn't do it accurately or quickly. LCD screens and flat panel displays didn't exist. Neither did the networked radio systems that allow communication among the vehicles and the mine managers."

Electronic componentry

Many of the components that are standard on the mining equipment of today didn't exist when the partnership began researching autonomous technologies two decades ago. For example, electronic control modules and embedded controllers are standard features on every wheel loader, excavator or truck made today. When the research began, machines had mechanical controllers—not electrical.

Similarly, machines used hydraulics instead of electro-hydraulics; sensors that are now available at the time were expensive, low capability and temperamental; and the algorithms, software and processing that make autonomy possible were either poorly understood, or tentative at best.

Perception technologies

One of the biggest challenges in the development of autonomous mine sites is obstacle detection and avoidance. Early versions of obstacle avoidance systems caused a machine to come to a stop when it detected an obstacle—resuming motion only after the obstacle was cleared. More advanced technologies enable an autonomous machine to determine alternate routes around the obstacles it detects.

Significant advances have been made in these "perception technologies," which make it possible for a vehicle to look at its environment and recognize what it sees. "Any autonomous vehicle has to take in sensor data, then process it fast enough to plan a route and make adjustments," says McCord.

As autonomous fleets of mobile machines become more widely used and complex, the task of planning alternate routes to avoid multiple, and often moving, obstacles requires the development of unique and inventive methods to be successful.

"Radar sensors are one part of the perception equation, but a number of different sensors are required," says Verheyen. "Any single technology wouldn't provide enough information to make the truck work as a part of the total mining system."

Management of exceptions

A human operator processes information without even realizing it, and can handle exceptions; a truck cannot. "We must be able to manage exceptions with the software," says McCord. "For example, if an operator hears a strange noise, he'll take preventive action, such as reporting it to maintenance. So we must expand VIMS to include those items normally monitored by an operator. Likewise, an operator can see a flat tire on the truck ahead of him, so we are developing technologies that are able to monitor tires."

AN AUTONOMOUS HAULAGE SYSTEM

An autonomous mine site involves a lot more than autonomous trucks. While the technology exists to build a truck that can navigate a haul road, it has to be able to work as part of a mine site system—interacting with every piece of equipment and every person on the site.

"We're developing an 'autonomous haulage system,'" says Edwards. "It's not just a truck. It's the process, the truck, the office software, the infrastructure. It may include a drill, tractor, truck, etc. It will incorporate technologies like MineStar®, CAES and Aquila™, as well as radio communications and positioning technologies."

Site automation is much more than the machines or the technologies. "Caterpillar is approaching autonomy in a comprehensive manner, where everything is automated—from blasting to loading to hauling to site management," says Edwards. "It's a very different approach. All of the vision will not happen overnight but Caterpillar is laying the foundation for the fully autonomous mine to be there one day."

The successful implementation of these new technologies will require significant changes in people and processes. "Some mining customers believe the biggest challenge to introducing autonomy is not the technology, but the people and processes," says Murphy. "Oftentimes, engineers focus on the product, but fail to understand that people and processes must change if the technology is going to deliver value."

Recognizing that there will be new mining processes resulting from autonomy, Caterpillar recently announced a groundbreaking alignment with BHP Billiton—the world's largest diversified natural resources company—to develop an autonomous mining haulage system.

"This close collaboration will focus on Caterpillar building an autonomous haulage system that will tightly integrate with BHP Billiton mining processes," says Caterpillar group president Stu Levenick.

The two companies are launching joint development programs, which includes enhancing existing mining trucks by integrating them with robust autonomous sub-systems—many of which Cat has already proven in the marketplace.

THE BEST APPLICATIONS

Like any new technology, mine site automation will not immediately be relevant in all ways on all sites. Individual companies will have to distinguish which sites have the best circumstances for early adoption.

Companies may find autonomy most useful where:

- The location is most remote
- Labor is less available
- Operations are highly repetitive
- Operations are simple
- A new site is being developed or an existing site has significant expansion

"Of course areas like the frozen North, where there are new opportunities to mine diamonds and uranium, are extremely amenable to automation," Whittaker says. "But that's not to say a 40-year-old mine on the outskirts of a city, one that's already entrenched with human operations, would not be the right application to get started with autonomy."

THE PAYBACK

While development of an autonomous mine site will require more capital upfront than a traditional site, paybacks are rapid.

"There are some costs for familiarization and for the learning curve and for embracing the new capability," says Whittaker. "But there is an immense return on investment. Much of the componentry is already there. So the industry will get a lot for a little more. It's inevitable that they're going to embrace it."

THE FUTURE

Whittaker maintains that autonomous technology will move forward as quickly as the marketplace demands. Once a number of mine sites are onboard, other sites will work quickly to follow suit.

"Development is rarely paced by the technology," he says. "The technology is there, and it can be built very quickly and introduced in a product. Once the industry starts demanding it, it will go much faster."

"It can become such a value-add and such an important competitive edge that it becomes something you can't be without," he says. "It will quickly go from being folly to being fundamental. It is something that pretty quickly mining companies won't do without."

BUILDING AN AWARD-WINNING AUTONOMOUS VEHICLE

Caterpillar has partnered with Carnegie Mellon University for decades, working together to build technologies and develop innovations that are the building blocks of autonomous haulage.

That partnership also includes Caterpillar sponsorship of the award-winning "Boss," an autonomous Chevrolet Tahoe that won first place in the 2007 DARPA Urban Challenge. The competition is sponsored by the Defense Advanced Research Projects Agency to help the United States defense department develop a fleet of autonomous ground vehicles to improve troop safety.

The Urban Challenge featured autonomous ground vehicles maneuvering in a mock city environment, executing simulated military supply missions while merging into moving traffic, navigating traffic circles, negotiating busy intersections and avoiding obstacles.

CMU and its Tartan Racing group received a US$2 million cash prize along with the recognition as a national leader in robotic engineering. The victory was based on three criteria: data collected during the competition, race time, and the ability to comply with traffic laws.

"Team Caterpillar is tremendously proud to be involved as a sponsor of CMU's Tartan Racing team," says Tana Utley, vice president of Caterpillar's Technology and Solutions division. "This victory represents what can happen when business and academia combine forces and work toward a shared goal of advancing technology."

As part of the sponsorship, Caterpillar provides advanced technologies such as drive-by-wire steering, sensing and software. In addition Cat has an embedded engineer working full-time with CMU's Tartan Racing team. Electronics control the engines and Caterpillar's Morelectric™ system generates the electrical power and air conditioning for the on-board navigation, control and guidance systems."

Team leader William "Red" Whittaker, a CMU robotics professor, says Caterpillar's business of developing innovative equipment to performing rugged work conditions made the company the perfect partner in this project.

Nearly 60 participants applied for the event, with the field narrowed to 11 finalists following a series of qualifying events. Also receiving high honors was Caterpillar-sponsored Virginia Tech's "Odin," which took third place, and Oshkosh Trucks "TerraMax," one of the finalists.

In addition to the benefits of participating in the development of the technologies used by its sponsored teams, Caterpillar benefits from the other teams as well.

"We're leveraging the knowledge of all the teams," says Utley. "DARPA gives us access to the brightest minds in the world, and we're taking that knowledge back to Caterpillar and using it in our machines."

Sponsoring the teams also allows Caterpillar to build actual components and test them in real environments. "We're using these vehicles as a test bed for the technology," says Utley. "It's a different approach to product and technology development and it's working."

Boss is a 2007 Chevy Tahoe that uses 19 sensors of six types to perceive its surroundings. Software running on 10 blade computers uses the sensor input to build a model of Boss' environment and to choose an appropriate set of actions for each road and traffic situation.

Boss is equipped with more than a dozen lasers, cameras and radars to view the world. High-level route planning determines the best path through a road network. Motion planning requires consideration of the static and dynamic obstacles detected by perception, as well as lane and road boundary information, parking lot boundaries, stop lines, speed limits, and similar requirements. Boss handles surprises such as other vehicles running a stop sign or making sudden stops or turns. Defensive driving skills allow Boss to avoid crashes.

Technology enables Boss to:

- Follow rules of the road
- Detect and track other vehicles at long ranges
- Find a spot and park in a parking lot
- Obey intersection precedence rules
- Follow vehicles at a safe distance
- React to dynamic conditions like blocked roads or broken-down vehicles

Each of the semifinalist teams had to demonstrate technical prowess to get invited to the event, but Tartan Racing believes that it has several characteristics that set it apart:

- Rigorous testing. Tartan Racing used two identically prepared vehicles to double the team's testing capabilities, logging more than 2,000 autonomous miles during more than six months of rigorous testing.
- Analysis tools. Tartan Racing has developed tools that allow team members to rapidly identify and correct problems that arise during testing. "Just as a good football team improves itself by watching film of its games, our system allows the team to visualize the vehicle's performance during tests," Whittaker says.
- Sponsors who are embedded on the team. The Boss' sponsors were active participants, working side-by-side to solve problems. Caterpillar has an Automation Center near Carnegie Mellon University which provided strong support to the team, including an embedded engineer.