

Next Generation System for Unmanned LHD Operation in Underground Mines

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ABSTRACT: In the pursuit of increased safety the mining industry has worked to develop systems for remote control and autonomous operation of both stationary and mobile equipment. This paper reports on a newly developed system for teleoperation and autonomous tramming of LHD (Load-Haul-Dump) mining vehicles that not only increases the safety of the operators, but also has the potential to increase productivity.

INTRODUCTION

In recent years, many solutions for improving the safety of LHD (Load-Haul-Dump) vehicle operations have been developed. Examples of these include line of sight remote control, video remote control and teleoperation. Unfortunately these solutions often result in reduced productivity compared with that of a machine that is driven by an on-board operator. However, very recently, new techniques have been successful at uniting the best of two worlds, combining the high safety of teleoperation while at the same time maintaining or even improving productivity as compared with a manual operator, by applying autonomous tramming and dumping capabilities.

In this paper we describe Atlas Copco's Scooptram Automation system, a complete teleoperation solution that includes both autonomous tramming and dumping. In the development of the Auto Tram function, large efforts have been made to create a system that not only has high performance and robustness but is also flexible and easy to handle. The high performance and robustness characteristics of the Auto Tramming system were previously reported on by Marshall et al. (2008).

In addition to the performance and robustness requirements, another goal has been to develop an automation system that can be handled by ordinary LHD operators, not only when it comes to operating the machine but also be able to deploy the automation system in a new area. Today this goal has been achieved with an automation system that offers productivity that is similar to or better in comparison with manually operated vehicles. An operator can easily set up the system for autonomous tramming in a new area, once standard WLAN communication has been installed.

In this paper, we describe the hardware and interfaces of the Scooptram Automation system, as well as the implementation and handling of the Auto Tramming system. A report on field-testing of the Scooptram Automation system is also presented at the end of the paper.

DESCRIPTION OF THE TELEOPERATION SYSTEM

Atlas Copco's Scooptram Automation system consists of an LHD vehicle prepared with extra sensors and WLAN communication capabilities at the remote site and an operator station (OPS) at the local site. An External Safety System and ruggedized standard network components are also offered with the system, but not required. The system includes both traditional teleoperation as well as an infrastructureless Auto Tram and dump system. Standard TCP/IP communication is used for the control streams between the machine and the OPS. There is no upper limit to the distance between the machine and the operator station, given that TCP and UDP communication with reasonable delay between the two sites exist.

Machine Installation Kit

To enable teleoperation and autonomous tramming of the ST14 Scooptram, the vehicle has been equipped with a set of extra sensors and communication capabilities; see Figure 1. On the sensor side this includes: an odometer (1) that measures displacement based on the rotation of the transmission drive shaft; a hinge angle encoder (2); two laser range scanners, one for each direction of travel (4); and, an IMU (Inertial Measurement Unit) (5) to help improve odometry. Video feedback to the operator is provided by up to four video cameras. Of these four cameras, at least two are facing forward (6, 7), mounted on different locations on the machine, while at least single camera is facing backwards (8).

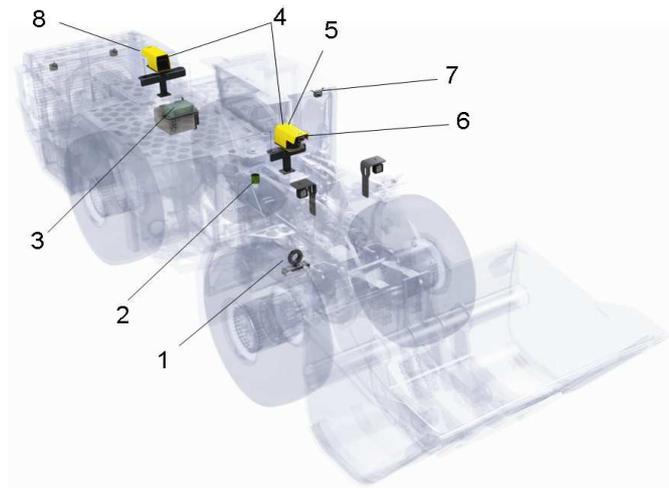


Figure 1. The ST14 vehicle installation kit of the Atlas Copco ST14 Scooptram Automation System: (1) Odometer, (2) Hinge angle encoder, (3) VCG (Video Communication Gateway), (4) Laser scanners, (5) IMU (Inertial Measurement Unit), (6) Front Camera, (7) Loading view camera, (8) Rear camera

The two laser scanners (4) are not only used to enable autonomous tramming, but also provide additional information to the operator about the machine environment in teleoperation mode. Each laser range finder measures the distance to the tunnel walls in a horizontal plane and thus together they offer a bird's eye view of the surrounding tunnel profile in the vicinity of the machine; see Figure 4.

To enable communication between the LHD-vehicle and the operator station, the teleoperation package also includes a VCG (Video Communication Gateway) (3) enabling fast and reliable roaming between access points, something that is not covered by the standard 802.11g protocol. Due to this module, no proprietary infrastructure needs to be installed in the mine. Instead, standard third party access points, switches, and routers can be used to provide the communication between the vehicle and the operator's station. The VCG is also responsible for streaming the video from the selected camera and sending it to the operator's station.

Running in parallel to the ordinary control system and control channels, the machine is also equipped with an external safety system that ensures that there is no single point of failure that prevents stopping the machine in case of emergencies.

Operator's Station

The Operator's Station (OPS) consists of a control panel, control panel monitor, and a server cabinet. The server cabinet contains the computational modules of the OPS, which are used to send commands to the machine and to process and display feedback to the operator. All hardware of the OPS, except for the monitor, is based on Atlas Copco standard RCS components, a guarantee for safe and trouble-free operation. The control panel is designed for excellent ergonomics, and shares components with Atlas Copco's Radio Remote Control (RRC) panel.

Also included in the Scooptram Automation system is a PC-based administrative computer connected to the operator's station and mounted in the server cabinet. This computer provides an interface between the Scooptram Automation system and the different production systems of the mine, and can be used to access production log files from the machine. Moreover, this computer is also used when deploying the Scooptram Automation system in a new area to administer the routes used for autonomous tramming and dumping.

Control panel

The control panel, shown in Figure 3, is equipped with two 2-axis proportional joysticks (1, 2) for controlling vehicle motion, and several push buttons for event based commands; e.g., releasing the park break or to start and stop the engine. One of the buttons is dedicated for activating and disengaging the Auto Tramming. The control panel also includes a jog-dial (3) used for menu navigation and selection. Both joysticks are equipped with three push buttons that are utilized for selecting direction of motion and to choose displayed camera view.

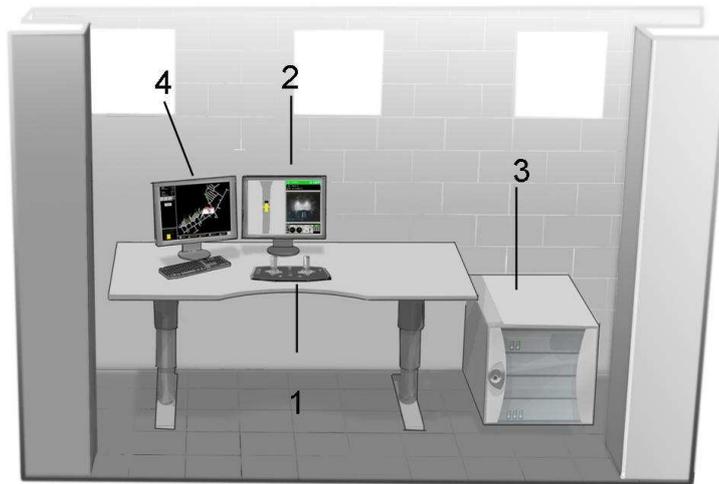


Figure 2. The Operator's Station of the Atlas Copco Scooptram Automation system: (1) Control panel, (2) control panel monitor, (3) server cabinet, (4) monitor for the administrative computer



Figure 3. Operator's station control panel with joysticks (1, 2), jog-dial (3) for menu selection and push buttons for event-based commands

Contrary to many other LHD teleoperation solutions, our system is designed so that the driving direction of the machine (forward/backward) is selected with the push buttons on top of the left joystick, instead of with the location of the joystick itself. This has the benefit that when pushing the joystick forward towards the display this will always correspond to the driving direction as displayed in the video stream. For instance, when reverse gear is selected, the display shows the video stream from the camera facing backwards. When the operator wants to start moving, he pushes the joystick forward towards the display where the video stream shows the machine moving deeper into the displayed image. This, in combination with inverted steering when driving in reverse, means that the movement in the video stream always reflects the movement of the joystick. In other words, pushing the joystick to the right corresponds to the vehicle turning to the right in the display, regardless of the selected direction of movement.

Control panel monitor

The control panel monitor is vertically separated in two different fields, as shown in Figure 4. On the right side, the video stream from the selected camera provides visual feedback to the operator. The displayed video stream is synchronized with the current direction of movement of the machine, unless the operator has selected another camera. The right side of the screen also has fields for system state information, warnings and errors, as well as a set of gauges corresponding to those of the display onboard the machine.

In addition to the basic video and system state teleoperation cues, half of the control panel monitor is reserved for the Laser View, which displays data from the laser range scanners. Here, data from both the front and rear laser scanner are fused using information from the articulation angle sensor and selected direction of movement. This creates a local track-up representation of the environment as perceived by the lasers. This multi sensor display layout has proven to be very useful for both inexperienced and experienced operators.

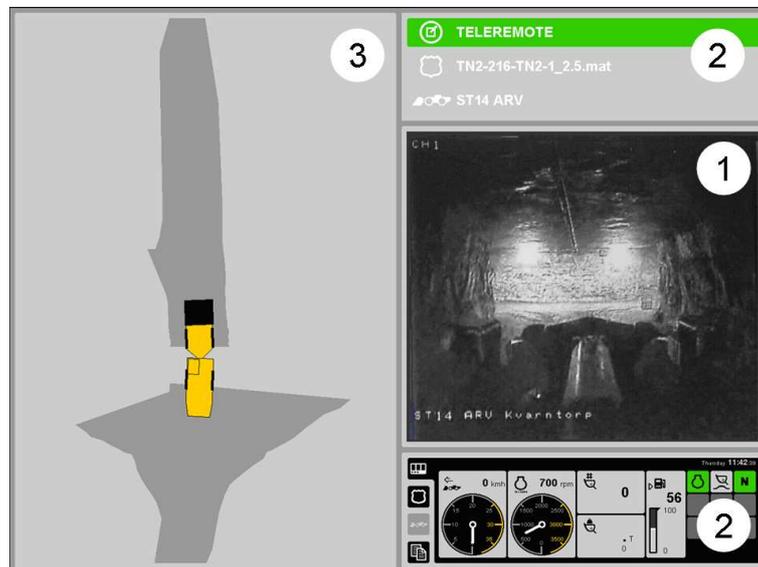


Figure 4. Control panel monitor displaying video stream (1) and status information (2) to the right; the laser view (3) to the left displays the machine (yellow) in the centre, with the black rectangle representing the bucket. The dark grey areas in front of and behind the machine are driveable areas as sensed by the laser scanners; note that no laser information is available in the longitudinal centre of the machine due to the limited field of view of the laser scanners

THE AUTO TRAM SYSTEM

From a technical point of view, the Atlas Copco Auto Tram system is based on a three-step approach: Teach, Route profile, and Playback. During the teaching step, an operator drives the vehicle along a desired route, either on the vehicle, or by teleoperation. Simultaneously, sensor data is collected and stored in a binary log file (front and rear laser rangefinders, hinge angle, displacement, and IMU). In the route-profiling step, data logged during the teaching step is processed (offline) and converted into a format suitable for use by the estimation and control algorithms during playback. The output is referred to as a “route profile” file, which contains information about the travelled path, a sequence of overlapping metric maps along the path, a record of any pause points (e.g., for dumping/loading material), as well as a vehicle speed profile to be tracked during playback. Finally, in the playback step, the system autonomously plays back a route profile generated by the teaching and route profiling steps. During playback, navigation and guidance algorithms use data from the specified route profile to estimate longitudinal, lateral, heading, and vehicle speed errors at discrete instants. The control system then stabilizes these errors so that the vehicle follows the profiled path at the desired speed.

Once profiled, a route can be played back many times and re-profiling would only be necessary if significant changes to the environment were made; e.g., due to significant mine development. Since the vehicle is driven along a collision-free path during teaching, complex path planning is not required. However, the system does include short-range guidance algorithms designed to stop the vehicle should the profiled path be subsequently obstructed during playback. Of course, these algorithms require that the obstacles are detectable by the laser scanners. The route profiling and playback steps are discussed more in Sections **Route Profiling** and **Playback**.

During the development of the Scooptram Automation system, an important goal was to create an Auto Trammng functionality wherein the complete procedure—from teaching a new path, to autonomously playing back the corresponding route in full production—could be handled by someone with only minimal experience with using a computer, but with good knowledge of the mine environment and how to operate an LHD. How this has been achieved is further described in Section **Route Administration**.

Route Profiling

A route profile consists of four components: a path profile, a pause profile, a sequence of locally consistent metric maps, and a speed profile. Firstly, a sequence of locations that are equally spaced (typically 0.5 m) along the path are created, called “path points”. We then associate with each path point the configuration of the vehicle at that point during the teaching step by interpolating the pre-processed logged data. Thus, the sequence of path points and associated data comprise what we call the “path profile”.

Metric maps of the mine environment along the path profile are generated by using both odometry and rangefinder data. Each map is an occupancy grid (Elfes and Moravec 1985). For localization in underground mines, this approach is much more flexible than a system that must classify tunnel topology in that it will work regardless of the shape of the walls, so long as the maps are of sufficient resolution. However, the use of a single monolithic map to represent the mine environment suffers from two key problems. Firstly, in some situations high memory usage is required. Secondly, map inconsistencies can result on longer traverses when a vehicle closes a loop or crosses its own path. For example, this can be seen near point 17 in Figure 5 where two drifts appear in the map where there is actually only one drift in reality (see map 18 on the left of Figure 5).

To address these problems, we employ a sequence, or “atlas”, of metric maps attached along the path to form an overall route profile; which is to say, the system does not rely on one monolithic map and an absolute frame of reference. The underlying idea is to create a situation in which the vehicle’s path exists in a high-dimensional space wherein it never intersects itself (Howard 2004). Figure 5 shows a monolithic map and the corresponding atlas maps generated from data acquired during an actual field test of the Scooptram Automation system. The monolithic map has a cellular resolution of 0.3 m, while the atlas maps each have a resolution of 0.1 m.

Playback

Our objective was to create a system that permits a large articulated vehicle to robustly track the path specified by a route profile. During playback, this has been achieved through the design of a two-timescale control system. At the slower timescale, or “outer loop”, are localization and path-tracking algorithms that work to reject lateral and heading path errors. At the faster timescale, or “inner loop”, are rate estimators and two controllers that track reference steering rates and vehicle speeds. The underlying justification for this two-timescale design is founded on the assumption that we can specify sufficient bandwidth separation between the nested control loops. A schematic of this control system architecture is shown in Figure 6.

At the outer loop, there exist two basic algorithms: localization and path tracking. The localization problem solved here is one of estimating the vehicle’s pose as it travels through a (locally) known environment. Recently, a number of techniques have been developed in the mobile robotics community that globally localize a robot in a known environment. Many of these techniques use a particle filter representation of the vehicle’s pose (Thrun et al. 2001). An initial design using a particle filter was shown to work in simulation, but required the use of too many particles (e.g., greater than 100) for convergence from a reasonable initial pose estimate. Variations requiring fewer particles and computational resources exist, but are complex to implement. Moreover, the task at hand does not actually require a solution to the global localization problem. Instead, we chose to implement a variation of the Unscented Kalman Filter (UKF) (Julier and Uhlmann 1996; Wan and van der Merwe 2000) to position with respect to the locally consistent atlas maps defined during route profiling. The inputs to the UKF algorithm are the laser rangefinder data as well as wheel odometry (i.e., hinge angle and wheel speed); the final outputs are heading and lateral errors of the vehicle with respect to the profiled path.

Briefly, the unscented transformation works by parameterizing mean and covariance information in a way that allows for propagation through a nonlinearity. This is done by creating a discrete approximation that can be directly transformed, which has the same mean and covariance as the original Gaussian. This approximation takes the form of a set of $2n + 1$ so-called sigma points (where n is the dimension of the configuration space of the vehicle), which are symmetric and have the desired mean and covariance. In our case, $n = 3$ because we are interested in estimating the vehicle planar position and orientation.

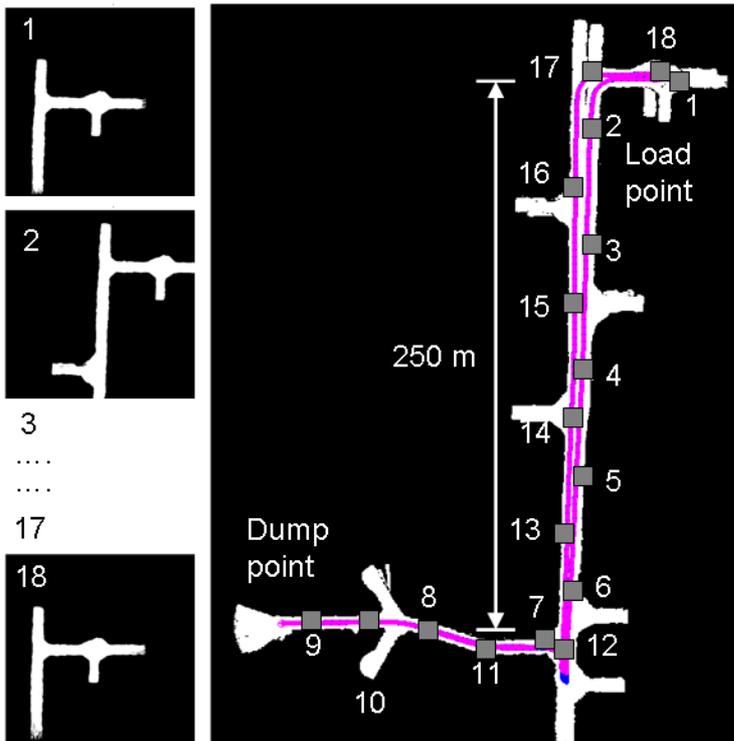


Figure 5. Example monolithic occupancy grid with atlas maps and vehicle path shown; the grey squares indicate the atlas map centres in relation to the driven path

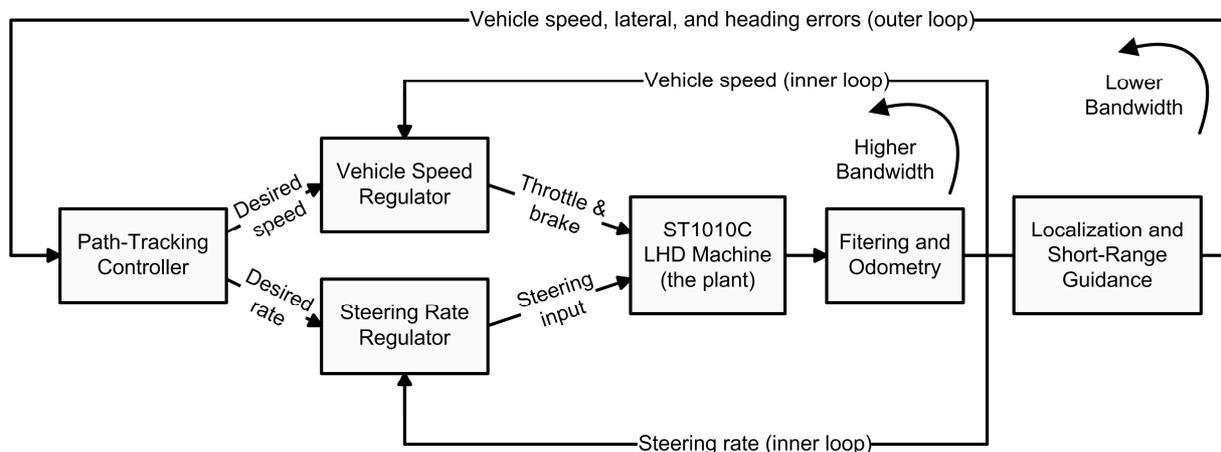


Figure 6. Two-timescale control system architecture

A path-tracking controller is required to guide the vehicle along the path specified by the route profile. Path-tracking control for articulated vehicles has been extensively discussed in the engineering literature, yet there is some disagreement over the form such a controller should take. Some researchers argue that the position of both front and rear components of the vehicle should be tracked; others suggest that wheel slip should be explicitly accounted for (Ridley and Corke 2001). We have found that, in practice, neither of these tasks is necessary under the two-timescale control architecture if inner-loop controllers are robust enough to handle these model uncertainties. Moreover, we have found that rejection of only the heading error and lateral error of the front component (when travelling forward) is necessary. We obtain these error signals from the UKF algorithm and then employ a nonlinear controller, based on feedback linearization, to drive them to zero, thereby forcing the vehicle to track the profiled path.

Route Administration

One of the goals in the development of Atlas Copco's Auto Tram system was to create a system so easy to handle that it can be administrated by LHD operators and ordinary service personnel from the mine. To achieve this goal, not only was it necessary to automate the actual tramming of the machine, but also it was necessary to automate the procedures for start-up and commissioning of the Scooptram Automation system in a new area. In other words, once an area has been prepared for automation with the required communication infrastructure, the procedure to teach, generate and playback new routes should be so easy to handle that almost anyone can do it.

In Atlas Copco's Auto Tram system this has been solved through dedicated software, which automates the complete procedure to validate a taught path and ensure that the system will be able to play back the route with high precision. This software, called "RouteManager", runs on the administrative computer included in the operator's station. With the RouteManager the procedure to go from an automation-ready area (i.e., prepared with communication infrastructure) to running Auto Tram in full production consists of five steps:

1. Teaching
2. Route Generation
3. Supervised Playback
4. Route Commissioning
5. Unsupervised Playback

The teaching step is the same that has been described previously, while Route Generation corresponds to route profiling but with additional sub-steps where the generated route profile file is analysed with respect to its suitability for autonomous playback. Supervised Playback and Route Commissioning consist of an iterative procedure where a newly generated route profile file is played back several times at increasing speeds and where the performance of the vehicle at a certain speed is analysed before the path can be played back at higher speed. The final step, Unsupervised Playback, is when the route is played back in full production. Steps 2 through 4 are implemented in the RouteManager software, and are detailed below.

Route Generation

Route Generation more or less corresponds to route profiling, but with the addition that the generated route file is analysed with respect to whether the recorded path is suitable for autonomous playback, in addition to assessing the map quality. Once the generation of a new route profile file has been initialized, the RouteManager guides the operator through the procedure by presenting a sequence of menus with information about the quality of the route and recommendations about whether the route should be approved or not. The output of the Route Generation procedure is a route profile file that is verified to be suitable for supervised playback on the vehicle.

In the path approval step, the route is simply analysed with respect to distances to obstacles—e.g., tunnel walls and ditches—to ensure a certain tolerance to path tracking deviations when playing back the route. The evaluation of the map quality is slightly more complicated. For instance, there are a few pathological situations in which the teaching and route profiling processes result in inconsistent maps. These situations can be difficult to detect, even for someone with an intimate understanding of how the navigation system works. These inconsistencies can result in degraded performance when playing back the route, or that the vehicle stops completely due to low localization certainty, which is not desirable. To detect and prevent these problems we have developed algorithms that analyse the generated maps with respect to correctness and consistency, which also detect if there are certain locations along the path where improvements can be made to the tunnel environment to achieve better performance of the Auto Tram system.

The analysis is presented to the operator as a graph of the map quality along the path, as well as a textual recommendation about the route profile's suitability for playback. An example of this is shown in Figure 7. If the RouteManager detects that there are problems with the maps, the corresponding areas in the tunnels can be identified in the map quality graph.

Supervised Playback

Supervised playback is used when a new route is run in Auto Tram for the first time. This simply means that the operator needs to pay attention to the vehicle behaviour and stop the machine if something unexpected occurs while playing back the route. When the route has been successfully played back and the vehicle has stopped at the route's endpoint, the route administration procedure moves on to the next step, Route Commissioning.

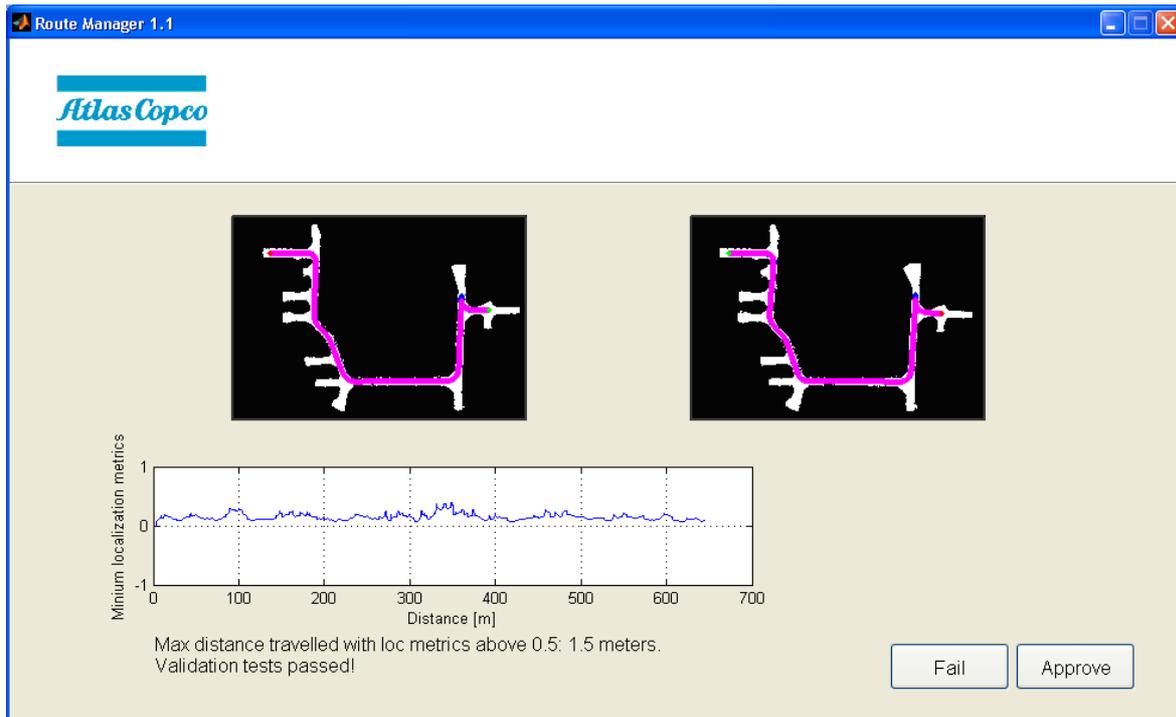


Figure 7. An example of the map approval menu; the textual recommendation is presented along with a monolithic map of the route and a graph displaying the map quality along the path; two different maps are displayed for the route to respective from the dump point

Route Commissioning

During supervised playback the vehicle automatically stores sensor data as well as internal states of the control system in a file. In the route commissioning step, this file is retrieved from the vehicle by the RouteManager software and analysed with respect to path tracking performance. If the path tracking deviation is below a certain threshold, the route is considered safe to run in unsupervised playback. Moreover, when a route has been commissioned at low speed, a new version of the route profile file with higher allowed maximum speed is made available on the operator's station for supervised playback. The supervised playback and route commissioning is thus repeated at higher and higher speeds until a route corresponding to the vehicle's top speed has been commissioned. Alternatively, the process is aborted when the route/speed combination fails the route commissioning process. When route commissioning is completed, the version of the route file with highest speed that has been commissioned is available on the operator's station for unsupervised playback.

Unsupervised Playback

Once a route has made it through route commissioning, it is considered safe for unsupervised playback. In other words, the route can be played back autonomously without an operator watching the progress and behaviour of the vehicle via the operator's station. We have found that this is sufficient to ensure reliable playback of the route in full production due to the high repeatability of the Auto Tram system (Marshall et al. 2008).

THE AUTO DUMP SYSTEM

In addition to the teleoperation and Auto Tram functionality the Atlas Copco Scooptram Automation system also includes functionality for autonomous dumping. This Auto Dump functionality is completely integrated with Auto Tram and allows automated dumping with high precision. The location of the dump point is taught by the operator during the route teaching procedure. In addition to the location of the dump point, the autonomous dumping procedure is parameterized to enable adjustments of the dumping to local conditions; e.g., berm height and number of times to "shake" the bucket.

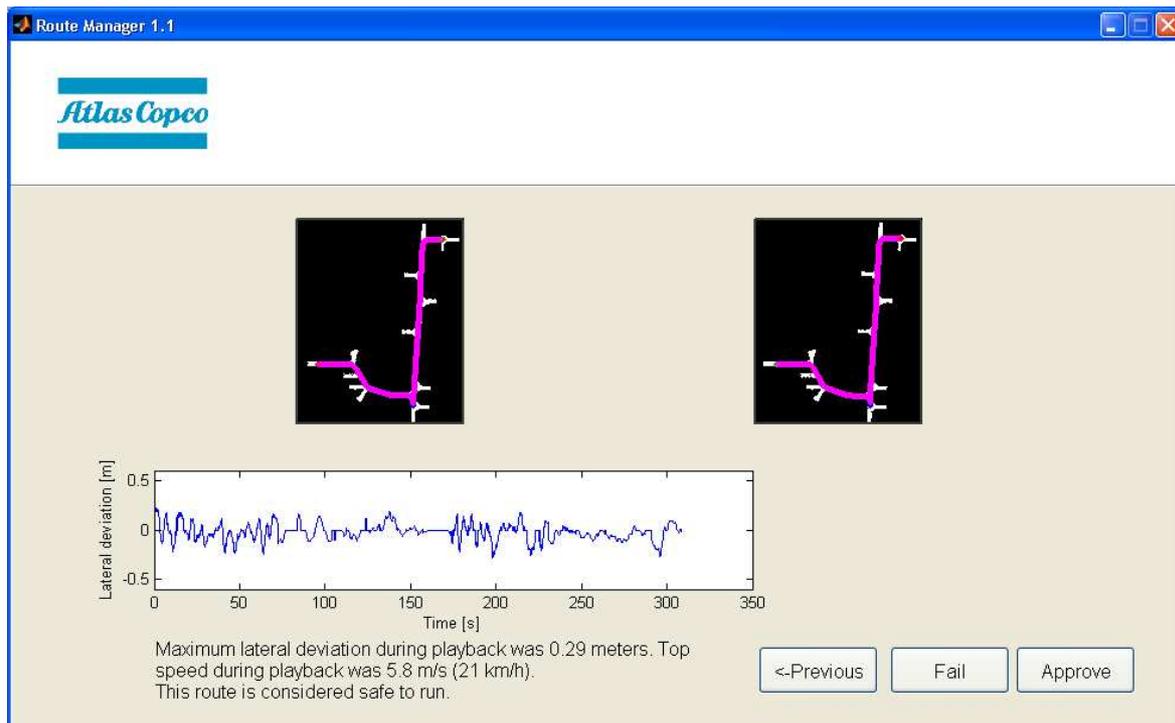


Figure 8. Route commissioning with the path tracking approval menu; the menu displays monolithic maps of the path to and from the dump point, a graph of the lateral deviation during the tram, and a textual recommendation of if the path is safe to run or not. In this case the path is considered as safe

FIELD TEST RESULTS

The Scooptram Automation system has been extensively tested, both in system verification tests (Marshall et al. 2008) performed in Atlas Copcos test mine in Kvarntorp, Sweden and in a field test at Outokumpu's mine in Kemi, Finland. The Auto Tram system was initially designed with normal production in mind; i.e., loading in a stope and dumping in an ore shaft. In the field tests however, the machine was used in a back filling operation where the system's flexibility and user friendliness were really put to a test. The field tests started in December 2007 and ended in December 2008.

In the Kemi mine a standard WLAN network is installed to enable communication via IP-telephones that are used both above and below ground by all personnel in the mine. During the initial installation, the Scooptram Automation system showed one of its major benefits: the utilization of standard WLAN communication components to provide communication between the machine and the operator station. No hardware modifications were required to enable the machine and the OPS to communicate through the mine's standard WLAN network. This strength was confirmed by frequent changes of the operating area between different levels and areas of the mine. Deploying the machine in a completely different area only required reconfiguring the access points of the new area to single channel operation.

Due to the very high production rate at the Kemi mine during the field test, it was not possible to seal off an area for automated operations for long periods of time. Thus, the Scooptram Automation system was often inactive. Nevertheless was the machine ran more than 1440 km and 28 500 tonnes of waste rock was backfilled in teleremote and autonomous mode.

The peak of the field test was in September 2008, when the Outokumpu performed an evaluation of the Scooptram Automation system and compared the performance to their ordinary loader and truck operation. During this period the machine was utilized extensively in autonomous mode, at one time more than 60 hours straight with pauses only for refuelling. In the last critical shift of these 60 hours the machine was driven continuously in Auto Tram with auto dumping. The machine stopped twice (communication timeout) due to a temporary but general problem in the mine LAN, while the Auto Trammig and dumping worked flawlessly. The main conclusion from the study was that the productivity of the automated machine was similar to, or better, compared to a manual operator.

The Scooptram Automation system was compared to an on-board manual operator driving exactly the same 2×225 m long route with the ST14 Scooptram. This comparison showed that the productivity of the automation system is equal to or slightly higher than the productivity of the manual operator for the evaluated application.

Outokumpu's estimated maximum capacity of one ST14 Scooptram Automation vehicle was 1662 tonnes/shift at a distance of 255 m. This figure should be compared to Outokumpu's traditional system with manually operated loader and trucks, where one loader and three trucks have a capacity of 3621 tonnes/shift at a distance of 220 m.

In the beginning of the field test, the RouteManager software was not available and all Auto Tram routes were generated, validated, and commissioned by Atlas Copco engineers. Once the RouteManager was available however, the task of teaching, generating and commissioning routes in a new area was completely handled by the ordinary on-site service personnel with support from LHD operators, proving the efficiency of the automated route administration.

A few times the ordinary backfilling operation of the mine was interrupted because of roof collapses and ground conditions not allowing manual operation in the unsafe areas. In these situations the automation system proved to be the safest method to maintain the area as well as to complete the backfilling task with high productivity.

CONCLUSIONS

The principal conclusion from the system verification and field tests presented in this paper is that the Atlas Copco Scooptram Automation system can certainly be a safe, efficient, and cost effective alternative to manually operated LHDs. In particular, the system has proven to be effective in unsafe areas where high productivity can be maintained by automated vehicle operations.

In addition to the high performance, robustness, and safety provided by the system, it is also easy to use. Ordinary on-site service personnel and LHD operators can perform both daily operations as well as deployment of the system in new areas of the mine. These personnel can not only to operate the vehicles through teleoperation, but also supervise and allow the system to operate in autonomous mode.

Another significant benefit of Atlas Copco's Scooptram Automation system is that it does not rely on any proprietary infrastructure—not for autonomous tramming, nor for ordinary teleoperation. The necessary communication between the operator's station and the machine is provided through standard WLAN, using third party of the shelf components.

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