Control of a Semi-Autonomous UGV using Lossy Low-Bandwidth Communication

Marco Langerwisch, Marko Reimer, Matthias Hentschel, Bernardo Wagner

Leibniz Universität Hannover, Institute for Systems Engineering, Real Time Systems Group, D-30167 Hannover, Germany
(e-mail: \{langerwisch,reimer,hentschel,wagner\}@rts.uni-hannover.de)

Abstract: This paper describes various mechanisms for supervisory remote operation of an UGV. Contrary to common Wi-Fi (IEEE 802.11) approaches our approach enables communication via a lossy low-bandwidth radio link. The mechanisms include the massive reduction of environmental sensor data for transmission to the operator. The vehicle itself is capable of semi-autonomous control. Doing so, the operator is removed from the high frequent vehicle control loop and maintains situational awareness.

Keywords: Teleoperation; autonomous mobile robots; environmental perception; low-bandwidth communication.

1. INTRODUCTION

In general, there are several ways to control a mobile robot. Depending on the specific task, the robot can be controlled directly in visual range (e.g. by a device like a joystick), some kind of teleoperation can be used, or the robot has to act full autonomously. When the mobile robot is not in line-of-sight of the operator, and autonomy is not available, a certain level of teleoperation will be the choice.

In this paper, we would like to present our approach to control our Unmanned Ground Vehicle (UGV) RTS-HANNA (see Fig. 1) at the European Land Robot Trial (ELROB (2009)).

The ELROB took place in different environments, especially in woodlands. Because of the short-range coverage it was not possible to use common communication techniques like Wi-Fi (IEEE 802.11) between vehicle and operator station. Therefore, we used a mid-range radio link, which features a lossy and low-bandwith data communication.

A lossy low-bandwidth radio link raises some special requirements to the (teleoperation) control system. The operator has to deal with high delays and gets only sparse information from the mobile robot. To avoid a move-and-wait (see Sheridan (1992)) behaviour, the robot has to be equipped with semi-autonomous capabilities which lead to a supervisory control mode instead of closed-loop control (direct teleoperation) (see Sheridan (1992) or Milgram et al. (1997)). Further, RTS-HANNA is equipped with several sensors to get an impression of its environment. These sensors are 2D and 3D laser range finders, a camera or GPS devices, for example. Ideally, the operator should have all this sensor information available. Because of the low-bandwidth of the radio link, it is impossible to submit all the recorded sensor data to the control station.

Our approach consists of a Graphical User Interface (GUI) at the operator site and several software-modules running at the UGV. To submit the available sensor information, it is heavily reduced. For navigation of the UGV, the operator sets waypoints in a geo-referenced map that are submitted to the mobile robot. In return, the operator gets various data consisting of environmental information, position information, and states of the UGV. An audio-visual feedback is also created by the GUI. For other examples see Fong et al. (2001), Ebken et al. (2005) or Kay and Thorpe (1995).

The following section gives an overview of the different modules involved in the control of the UGV. The radio link is subject of Section 3, while Sections 4 and 5 present our approaches to reduce the sensor data of the laser range finders, and the camera respectively. Section 6 deals with the graphical presentation of the environment and UGV states, and the supervisory control by the operator. Finally, Section 7 presents the results of some runs we conducted at the ELROB trials in 2008 and 2009. The paper ends with a conclusion.

![Fig. 1. UGV RTS-HANNA](image-url)
2. SYSTEM OVERVIEW

The complete system for semi-autonomous teleoperation of the UGV RTS-HANNA consists of several hardware sensors and actors, as well as software modules. This section gives an overview of the involved components and their cooperation. A graphical representation is given in Fig. 2.

The central software module is the TeleOp module. It collects the information and system states, assembles and forwards them to the radio link. The communication with the GUI consists of several message types and packages, which will be described further in Section 3.

To calculate the robot’s position, the data of GPS receivers are fused with the data of the Inertial Navigation System (INS). The INS consists of wheel odometry and a gyrometer. At the fusion stage, a Kalman filter is used. For detailed information see Hentschel et al. (2008).

Navigation of the UGV is primarily based on laser sensors. To get a broad overview of the environment, our robot is equipped with 3D laser range finders. To have the 3D data to be transmitted via the low-bandwidth radio link, the data volume has to be reduced. This is done by an approach called Virtual 2D Scan. In addition, a fast 2D laser range finder is mounted at the front bumper. The 2D data of all laser range finders are merged and further reduction of the scan points is done. This, and the virtual 2D scans will be described in Section 4.

In distinct situations, e.g., to visually check its environment, the operator is dependent on images of an onboard camera. Because of the high data volume, these camera images are heavily reduced (see Section 5).

After submitting the waypoints determined by the operator to the robot, TeleOp forwards them to PilotWaypoint where a route is calculated. PilotWaypoint sends velocity set points and steering commands to the Chassis. In between, an obstacle detection as part of the PilotWaypoint reads the merged laser range finder data and checks, whether an obstacle is in range. If this is the case, it slows down or stops the vehicle depending on the distance to the obstacle. Finally, Chassis submits some information about the vehicles status like current velocity, steering, or motor state to the TeleOp module.

3. RADIO LINK

The communication between the operator site and the mobile vehicle is triggered (polled). Instead of continuously sending data from the moving vehicle each message is requested from the operator site. This allows to detect a connection loss on-board the vehicle. When the connection is lost for a specified amount of time the vehicle can autonomously take actions to reestablish the link. For example, the vehicle can start going backwards on the known path until the link is up again.

Each reply message consists of different kinds of data (see Table 1). There are two types of large sensor data, laser scanner data and camera data. Additionally, there are small status information like the current position and the engine status. To minimize information loss a message consists of several independent data packages.

The different kinds of data have different requirements. For the status information it is important to be available with low latency. The operator needs to know the position, orientation and speed of the vehicle as direct as possible. So the overall latency must be kept low. To give the operator an impression of continuous information flow, we decided the information should be updated with about 1 Hz. Therefore the whole communication cycle of sending a request and receiving all data packages should not take longer than one second.

<table>
<thead>
<tr>
<th>Status</th>
<th>pkg</th>
<th>Scan2D pkg 1</th>
<th>Scan2D pkg 2</th>
<th>Camera pkg 1</th>
<th>Camera pkg 2</th>
<th>Camera pkg 3</th>
<th>Camera pkg 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status pkg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. LASER SCAN POINT REDUCTION

Our UGV is equipped with rotating 3D laser scanners based on SICK’s LMS291, assembling 3D raw point sets. An introduction to the scanning device is given by Wulf et al. (2007).

In the first subsection, a summary of the calculation of virtual 2D scans is given. The special virtual 2D scan we used for navigation and obstacle detection is shown in subsection 4.2, while a further reduction step is explained in subsection 4.3.

4.1 Virtual 2D Scan

Submitting full 3D raw point data sets via a low-bandwidth radio link in real-time is impossible. The aim of virtual 2D scans is to reduce these 3D point sets to 2D point sets.

Virtual 2D scans are calculated regarding a special purpose, e.g. localization or navigation (see Wulf et al. (2004)). For this special purpose, the raw 3D range images include many redundant and unnecessary information, or points respectively. Extracting points without losing relevant information and projecting them on a 2D plane reduces subsequent computational costs and data bandwidth.

According to Wulf (2008), virtual 2D scans are calculated in two steps. First, reduce the amount of points of the 3D point set S:

\[ f : S \rightarrow S_r, \quad \text{having} \quad S_r \subset S. \]  

The size of the new point set \( S_r \) is

\[ l = |S_r|, \quad \text{having} \quad l \ll |S|. \]  

Function \( f \) depends on the special purpose of the virtual 2D scan and will be defined in the next subsection.

In the second step the virtual 2D scan \( V_S \) is calculated from the reduced point set \( S_r \):

\[ g : S_r \rightarrow V_S \]
with \[ g : (x, y, z) \rightarrow (x, y), \quad x, y, z \in \mathbb{R}, \] where \( x, y \) and \( z \) are the \( x, y \) and \( z \) coordinates of a 3D point. Equation 4 projects the 3D points of the reduced point set \( S_r \) on the 2D plane. Provided that \( f \) fits the purpose of this reduction, all relevant information will be kept in the virtual 2D scan \( V_x \).

4.2 Outdoor Obstacle Scan

All relevant information included in the 3D scan and needed for navigation are the points that mark an obstacle for the mobile robot. Therefore, the ground level \( z_{\text{gnd}} \) of the environment is extracted from the 3D scan. An obstacle point is defined as a scan point higher than \( z_{\text{min}} \) and lower than \( z_{\text{max}} \) with respect to the ground level. Furthermore, the environment is checked for impassable slopes, i.e., slopes greater than \( \text{slope}_{\text{max}} \) in positive and negative direction.

A detailed description of the outdoor obstacle scan and virtual 2D scans is given by Wulf (2008).

4.3 Point Number Reduction

The aim of further reduction is to reduce the 2D scan with its \( n \) scan points to \( n_r \) scan points. Therefore, the 2D scan is split up into \( n_r \) sectors. One point with minimum radial distance to the robot is chosen per sector and added to the new reduced 2D scan. Additionally, the reduced scan is split into two separate data packages (see Table 1) to minimize the impact of package loss. Package one consists of sectors 1, 3, 5,..., and package two consists of sectors 2, 4, 6,... to keep a minimum of environment information in case of one lost scan 2D package.

5. REDUCTION OF CAMERA IMAGES

As stated in Section 3 a message must be sent within a communication cycle. The transmission of images using low-bandwidth with such a short communication cycle needs a strong data size reduction as images tend to be of relative large size. Additionally, the transmission may be lossy, so the system should provide as much information as possible from the received data. Thereby, the requirements of the operator change in different situations. While the vehicle is moving, it is most important to get information with very low latency to be able to react. As soon as the vehicle stops the time needed to transfer data is almost irrelevant but the level of detail within the images is important.

Summing up, the use of camera images by a remote operator needs three main aspects to be met:

1. low amount of data to be transmitted (subsection 5.1),
2. robustness against data loss (subsection 5.2),
3. adapting to low latency/high detail requirements (subsection 5.3).

5.1 Pixelwise Data Reduction

A great part of the information within a color image is not needed by an operator to navigate a vehicle. The operator is interested in structural information supporting decisions like wether a pathway is driveable or not. For example, the operator must be able to distinguish between road and not road. First of all the color information can be discarded. When using only grey levels one byte per pixel is sufficient, reducing the data of one image up to about 66 percent. Moreover, the operator is not interested in fine grey level, therefore the 256 grey levels provided by 1 byte can be further reduced. Depending on the situation 128 (7 bit), 64 (6 bit) or even less grey levels might be sufficient. For example, using 6 bit grey levels results in an additional 25 percent data reduction. These pixelwise simplification reduces the amount of data without a significant loss of information for the human operator (right image in Fig. 3).

For any further reduction an image compression might be considered. The possible kinds of compression methods include vector quantization, predictive coding and frequency based coding (see Ohm (1995)). Predictive coding is well suited to reduce the second and following images but needs a complete first one. Each first image is therefore still too large. The vector quantization and the frequency based coding are efficient in reducing the image size as long as static dictionaries can be used. If the dictionary is adaptive it must be transmitted. Doing so the data size is increased. Additionally, this methods suffer badly from a lossy transmission. If parts of a compressed image are lost, the whole image cannot be restored and no information is provided to the operator. As the operator should be able to visualize all received data, a lost packet should not influence any other packet. Therefore, a corrective code with additional data must be employed. As a result even the well-known jpeg-compression cannot achieve the needed packet size of about 1 kbyte/packet. Finally none of the compression methods is able to switch between the low latency and fine detail mode without manual interaction on a lossy transmission.

5.2 Image Splitting

Depending on the communication cycle time and the data rate on the radio link the maximum number of pixels per transmitted image is fixed. If the pixelwise reduction is not sufficient to transmit an image within a communication cycle, the image data must be split up into several messages. This splitting should automatically adapt to the low latency / high quality requirement while at the same time being robust against package loss.

Instead of using regions of interest and transmitting an image piecewise, we split up the image pixelwise to transmit information from all image parts within all transmissions. An image is split up into four subimages using the pattern shown in Table 2(a). Applied to an 8x4 pixel image, Table 2(b) shows the subimage indices of the individual pixels. For example, subimage 1 consists of all pixels marked with 1.

This pattern uses the fact that neighbouring pixels are often related. The ordering within this pattern is similar to the commonly used Bayer-pattern (Bayer (1976)) within color sensors. If an image is only transmitted partly the missing parts must be interpolated. A survey comparing several ways of interpolating this pattern is for example
The advantage of this recursive pattern becomes apparent when the communication is lossy. As data is not to be repeated and additional corrective data is not included in the communication, lost data cannot be repaired and the whole lossy data package is useless. Depending on the number of subimages used, the amount of information lost by one or even some subimages may be acceptable for a human operator. Additionally, longer packages are more often damaged than short packages. So it is advantageous to transmit several small packages than one big package. An image of transmittable size is therefore once more split up into subimages and all four subimages of this last splitting step are transmitted within one communication cycle (see Table 1). Table 4 shows the splitting pattern for two and three splitting steps. Summing up data loss cannot be repaired due to the extreme small data size, with no correction data. But as data packets are as small as possible the loss is minimized.

Table 2. (a) Splitting pattern (b) Pattern applied to an 8×4 pixel image

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. Number and size of subimages

<table>
<thead>
<tr>
<th>no. of steps (d)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel distance (p)</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>no. of subimages (I)</td>
<td>1</td>
<td>4</td>
<td>16</td>
<td>64</td>
<td>256</td>
</tr>
</tbody>
</table>

The Second IFAC Symposium on Telematics Applications - TA2010, 5-8 October 2010, Timisoara

5.3 Adaptive Resolution

To fulfill the different requirements on a moving and a stopping vehicle the system must detect these states. As long as the vehicle is moving a new image is taken every second. This new image is stored within some buffer and processed. As soon as the vehicle stops moving, the camera stops taking new images. The image processed does not change anymore and subsequent subimages transmitted add detail to the image at the operator site. This improvement is done continuously with every arriving subimage. As all subimages are indexed lost data does not affect received data. When all subimages are transmitted and the vehicle still does not move, all subimages are sent again, trying to fill lost data. Fig. 3 shows two images of almost the same perspective. The left image has been taken while the vehicle was moving. The image shows four of 64 subimages. The image is very rough but the main structures are visible. The right image shows the same situation after almost all 64 subimages have been transmitted.
6. GRAPHICAL USER INTERFACE

The Graphical User Interface (GUI) we use for control of our UGV is depicted in Fig. 4. It consists of several visual components and an audio feedback for the operator.

The map component is located in the upper half of Fig. 4. Different kinds of maps can be loaded into it, e.g. georeferenced satellite images or cadastral maps. Here, we used a map from OpenStreetMap (2009). According to the transmitted position and heading of the vehicle, a graphical representation of it is projected onto the map. The red dots mark obstacle 2D points in the environment of the robot (see Section 4). Finally, the operator can set, change and remove waypoints that are transmitted to the mobile robot. They are illustrated as blue circles in the map component.

In the lower left corner of the GUI the camera interface is located. The current camera image is encircled by three sliders to control the camera’s pan, tilt, and zoom, respectively.

The rest of the lower GUI component consists of some information about the connection, vehicle and mission status. For example, information about the velocity, heading and position in UTM coordinates is available. Two arrows mark the direction and distance of the operator station to the vehicle, and direction and distance of the vehicle to the global destination that has been determined by the operator in advance. The horizon at the right side of this component represents roll and tilt of the vehicle. Several buttons at the top of the component allow the operator to switch between different pilots, i.e. different behaviours, and other minor settings. All the command data like the values of the camera sliders, the selected pilot or current waypoints are transmitted to the vehicle with the data request message (see Section 3).

To support the operator the GUI provides an audio feedback via speakers or headphones. It codes the velocity of the vehicle into a frequency to give the operator information whether the vehicle is moving, and a feeling about the coarse velocity. This helps the operator to detect a stop or slow down of the vehicle because of reaching its last waypoint or obstacles in the environment without keeping an eye on the velocity display all the time.

7. APPLICATION

The communication system introduced in this paper was applied at the European Land Robot Trial (ELROB (2009)) in 2008 and 2009. In different scenarios, the system was used for semi-autonomous control of our robot RTS-HANNA (see Fig. 1).

The robot is based on an off-the-shelf Kawasaki Mule 3010 Diesel 4x4 side-by-side vehicle. Fully street licensed, this vehicle is equipped with a drive-by-wire retrofit kit from PARAVAN GmbH. This system enables manual as well as full computer control of the vehicle. The environmental perception is based on a pair of continuously rotating 3D...
laserscanner RTS-ScanDriveDuo with an update rate of 0.8Hz each. Additionally an Ibeo Lux laserscanner is used for fast obstacle detection within the main driving direction. In the context of the ELROB trials, the localization is based on a data fusion of GPS, wheel odometry and inertial data. Data acquisition and processing is performed on three embedded PCs. An additional embedded PC is used for data logging during the trials. For the radio link, a Satel Satelline 3-ASd Epic radio modem is used. Operating at a frequency of 433MHz in the unlicensed industrial, scientific and medical (ISM) radio band, the modem allows a maximum data rate of 19200bps. For application on a moving ground vehicle, the radio modem features diversity reception.

The operator station consists of a mobile telescopic radio mast with a maximum (secure) height of 10m. On top of the radio mast, an identical Satel Epic radio modem with a directional Yagi antenna is installed. The antenna has a directivity of 180° and an antenna gain of 6dBi. For visualization and vehicle control a laptop computer is connected to the radio modem via a serial RS232 interface. During all the ELROB trials, the operator station was set up at the predefined location and the radio mast was extracted to its maximum height.

7.1 M-ELROB 2008

The military ELROB was organized between 30th June and 3rd July 2008 in Hammelburg, Germany. The presented communication system was used for vehicle control in the scenarios Reconnaissance and Surveillance and Transport-Mule. For the Reconnaissance trial, 11 participants were given the task to reach a predefined destination in either 500m, 1km or 3km. The scenario was conducted in two parts, a qualification trial at daytime and the main trial at night. We chose the 1km distance and qualified as one of four teams for the main reconnaissance trial at night. At the night scenario we were the only team which participated at the 3km distance in a hilly and densely forested terrain. Before losing the radio communication after a knoll, the robot was able to drive 2.5km semi-autonomously along forest tracks. Trying to regain radio communication the robot managed to drive automatically 500m backwards on its predefined route before it got stuck in the forest.

7.2 C-ELROB 2009

The civilian ELROB was organized between 15th June and 18th June 2009 in Oulu, Finland. For vehicle control, the communication system was used in the scenarios Autonomous Navigation and Reconnaissance and Surveillance. The ELROB 2009 trials were conducted in a former zoo area. Wired fences, abandoned steel cages and dense forest were limiting wireless radio communication of all participants. For the Autonomous Navigation trial, 4 teams were given the task to follow a given route with a total length of 5.2km in a maximum mission time of one hour. Unknown to the operator in advance, the route contained challenging parts as a bridge crossing and a narrow forest passage. During this run, our communication system was able to transmit a total number of 775 full datasets, including camera image, 2D scan, position and status information from the robot to the operator via the lossy, low-bandwidth radio link. For this, a total of approx. 2MB of data were transmitted from the robot to the operator. During this trial, the maximum aerial distance between the operator and the robot was 1km. Fig. 5 illustrates the position of the robot during this run by a black line. Red dots mark the positions of successfully received radio transmission by the operator.

7.3 Future Work

The successful participation at the ELROB 2008 and 2009 trials demonstrates that the communication system can be used for controlling an unmanned ground vehicle semi-autonomously under real-world conditions. Applied to the presented trials, we were the only participant that was able to operate the vehicle over a distance of up to 2.5km in challenging environment using a terrestrial radio link. Please refer to the Elrob website for more details regarding the results (ELROB (2009)).

Considering the manual intervention time e.g. at the Autonomous Navigation trial at the C-ELROB 2009, the operator required a total of 24 minutes out of 60 minutes mission time to interact with the robot via the communication system. This interaction includes the analysis of the transmitted camera image, the laser scans and the setting of appropriate new waypoints. The reduction of this manual intervention time will be the focus for future work. This will basically be achieved by increasing the overall system autonomy. For this, the present navigation system will be enhanced by the capabilities of global path planning, improved reactive obstacle avoidance and global path replanning based on the mapped obstacle situation.
8. CONCLUSION

The aim of this paper was to present our approach to control a semi-autonomous Unmanned Ground Vehicle via a lossy low-bandwidth radio link. This approach included mechanisms to reduce the data volume of sensor data from 2D and 3D laser range finders, and a camera for transmission to the operator station. The laser range finder data were reduced by an approach called Virtual 2D Scan and a further point number reduction, and the camera images were recursively split into subimages by a special splitting pattern for sequential transmission.

We have shown the successful application of our approach at the European Land Robot Trials 2008 and 2009 where our UGV was able to drive up to 2.5km semi-autonomously along forest tracks without losing communication to the operator station. Future work will deal with the increase of the system autonomy to reduce manual intervention time by the operator.

REFERENCES


