Automation and Robotics in Construction XII
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ROBOT-MOTION IN UNSTRUCTURED ENVIRONMENT

Abstract

To operate an autonomous Vehicle in off-road terrain is one of the most difficult problems in Robotic. Since it is not possible to build a high resolution model (3d map) of an unstructured terrain, in particular of an industrial area or a construction site, a robot, driving through this terrain, has to be able to adapt its motion to the real world. In Dornier´s experimental program for "Outdoor Robotic Applications" therefore a key function is real time obstacle detection and avoidance. In conjunction with a gyro-system and an optical tracker this function ensures a cross-country driving on a pre-planned path by surveying the real world. Using an active (time-of-flight) laser-scanner a temporary 3d-image, consisting of 128 x 64 Voxels, is generated four times a second and real-time transformed into a 2d-obstacle-map. This map is used by the Navigation-computer to avoid obstacles while following the given path as close as possible.

A prototype of this system has been tested under real conditions in field-tests already.

1 AUTONOMOUS DRIVING IN OFF-ROAD-TERRAIN

One of the most important capabilities an Outdoor Robot-Vehicle has to have is the capability to move in any given terrain, including static and dynamic obstacles.

Since autonomous road driving has been shown already in various robot projects (e.g. ALV, GRS, Navlab, VaMoRs, ...) the efforts of Dornier´s experimental program on autonomous driving are concentrated on off-road-driving in unstructured terrain.

2 Robot Control

For fast operation of the Robot-Vehicle in the dedicated area and in order to simplify the Man-Machine-Interface (MMI) for robot control, most of the driving tasks (even for complex routes) will be controlled by only five single commands or by a pre-planned rout plan.

These drive commands are:

- Path Following
- Heading Mode
- Object Tracking
- Contour Tracking
- Road Following

Extra manoeuvres, such as small curves or backward driving, may be performed by means of a small set of additional commands.

2.1 Path Following Mode

Using a cursor on a digital map display, the Path Following Command will be generated by marking the goal-point and, if there are any, way-points on the path which the Robot-Vehicle has to meet on its travel.

After receiving this Command, the robot prepares itself autonomously for moving (e.g. starts the engine, looses the brake, ...) and starts driving to the goal-point - via all given way-points.

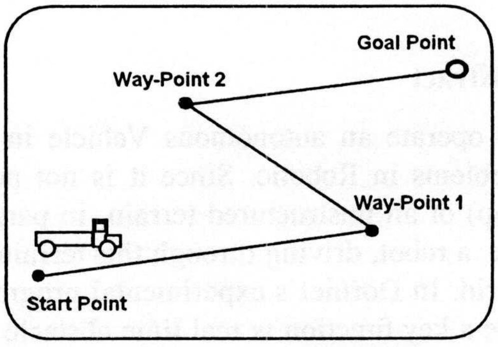

Fig. 1: Path-Following

Controlled by a dead reckoning navigation system with an associated north seeking gyro, the robot drives on "straight lines" between way-points and changes its moving direction at way-points without stopping.

2.2 Heading Mode

A Heading Command consists only of two information, the heading angle in respect to north and the distance to the goal-point in meters. The driving will be performed similar to Path Following on a "straight line". This Command is very helpful for alignment of the Robot-Vehicle into a required direction. Therefore, it mainly will be used for short distances only (5 m to 10 m) as an "appendage" to a Path Following Command to assure the required orientation of the robot.

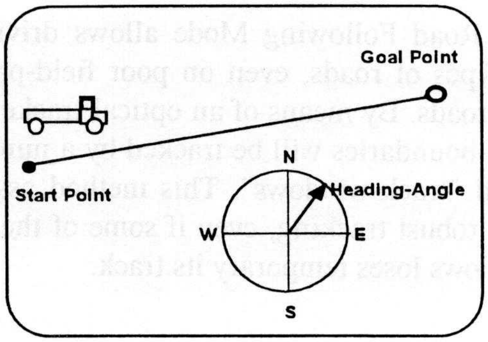

Fig. 2: Heading Mode

2.3 Object Tracking

In Object Tracking Mode the navigation is performed by an optical track system. On request of the operator, the Robot-Vehicle transmits a single TV-image from its front camera (drive corridor camera) to the control post. By setting a cursor on any object in this picture (e.g. a tree, a window in a wall, ...) the direction of driving is determined. After completion of the Track Command by the required driving distance, the Robot-Vehicle moves, again on a "straight line", for the given distance forwards the track goal.

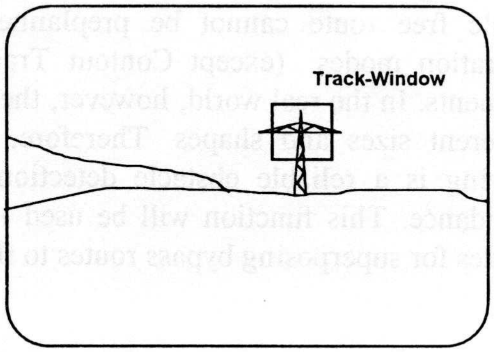

Fig. 3: Object Tracking

2.4 Contour Tracking

In Contour Tracking Mode the Robot-Vehicle follows any given contour (line) e.g. field edges, trenches or painted lines on the surface. The Contour Track Command will be performed similar to the Object Track Command, using a cursor in a TV-image.

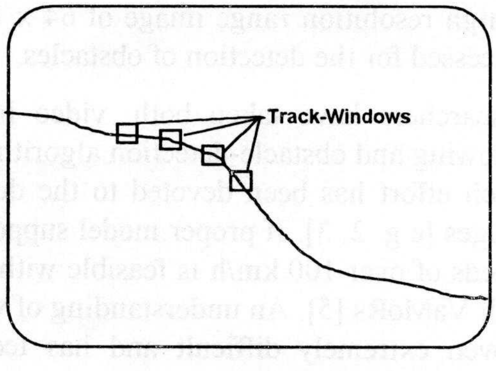

Fig. 4: Contour Tracking

2.5 Road Following

The Road Following Mode allows driving on all types of roads, even on poor field-paths or dirt-roads. By means of an optical tracker, both road-boundaries will be tracked by a number of small "track-windows". This method assures a very robust tracking, even if some of the track-windows loses temporary its track.

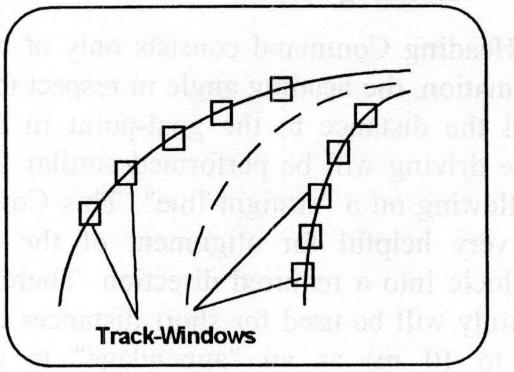

Fig. 5: Road Following

3 Need of Obstacle Avoidance

Since high resolution models or maps of unstructured terrain are not available, an obstacle free route cannot be preplanned. Taking this into account, all off-road operation modes (except Contour Tracking) are based on straight lines as route elements. In the real world, however, these straight lines will meet lots of obstacles in different sizes and shapes. Therefore, the most important function for off-road-driving is a reliable obstacle detection in order to perform a sufficient obstacle avoidance. This function will be used in parallel to each of the off-road operation modes for superposing bypass routes to the straight line route elements.

4 TECHNICAL APPROACH FOR OBSTACLE DETECTION

4.1 Range vs. Video Imaging

A 2-d scanning laser radar has been developed to serve as sensor in the vision system. A high resolution range image of 64 x 128 pixels is generated at a rate of 4 Hz and processed for the detection of obstacles.

Researchers have taken both, video images and range images as input to road following and obstacle-detection algorithms. Since video cameras are easily available, much effort has been devoted to the development of algorithms that process video images [e.g. 2, 3]. If proper model support is provided, video-based road following at speeds of over 100 km/h is feasible with little hardware. This has been demonstrated with VaMoRs [5]. An understanding of video images of off-road scenes, however, has proven extremely difficult and has led some researchers to support their vision systems with range sensors.

In passing from video to range imaging, the task of image processing is substantially alleviated at the cost of introducing a more complex sensor. It is clear why range images are simpler to process for ground/obstacle detection than video images. Navigation of a land vehicle is basically a geometric issue: the auto pilot needs to know the distance and directions of obstacles, the extent of navigable terrain stretching out before the vehicle, the inclination of grades etc. Such numerical data is directly obtained from range images by purely geometrical algorithms, without requiring a symbolic understanding of the scene. From a range-image, an obstacle can be detected, located, and avoided without knowing what the obstacle is. This is not true for a video-image. Geometrical information about the scene is only available when a model has been properly matched with the image, i.e. when the image has been understood. Model support is obviously an elaborate affair; while it is desirable for range image interpretation at an advanced level, it is not required in the present context.

4.2 Description of Sensor

The Dornier Laser Scanner performs a time-of-flight range measurement. A GaAs laser diode of wavelength 0.9 μ is used. The dual optics (for separate transmission and reception) are currently designed to provide a measurement range of 3 m - 50 m and a Field-of-view of 30° x 60° (vertical x horizontal). Typical range measurement accuracy is ± 0.5 %.

Eye-safety is guaranteed by supplying laser power only during active scan. The 2-d scan is currently mechanical in both directions (vertical and horizontal); however, electronic line scanners with 64 pixels have been in use at Dornier for some time, and this technology will be included in the future.

5 OBSTACLE DETECTION FROM RANGE IMAGES

This section presents an overview of the obstacle-detection algorithm implemented on the image processing unit of the vision system. Based on range images, this algorithm generates "maps of obstacles" that serve as input to the obstacle avoidance algorithm. Section 5.1 gives only a brief outline of this algorithm, as it has already been published in detail elsewhere [4].

5.1 Algorithm

Using a single range image and the associated vehicle state data as input, the algorithm generates a binary map of obstacles (Fig. 9). A map of obstacles constitutes a bird's eye view of the scene; the vehicle is represented as a small box at the lower center of the image.

Each pixel of an map of obstacles assumes one of three colours: black, green, or red. A green pixel represents an area of terrain which is navigable, a red pixel is considered inaccessible (either because it is obstructed or because it is excessively inclined); a black pixel cannot be assessed with regard to its navigability. No reference map or reference model is employed. The Map of Obstacle displays clusters of red pixels, i.e. "obstacles"; at the current level, the algorithm has no means of identifying such obstacles.

We shall briefly outline the major steps leading from a range image to an map of obstacles. Due to the knowledge of the current vehicle position and orientation, the range value associated with each pixel of the image may be transformed into a 3-d positional vector in absolute space. In this way, from the range image a set of points in 3-space is obtained. Each point indicates the position in 3-space where the laser pulse emitted in the course of an individual range measurement was reflected.

In the following, this set of points will be called "3-d image". The map of obstacles is derived from the 3-d image without further reference to the original range image.

The 3-d image represents a silhouette of the scene scanned by the sensor. No attempt is made to fit surfaces to the 3-d image. Instead, a set of simple geometric rules [4] is applied to each data point which directly correlate this point with neighbouring points. The result of this correlation may lead to a colour label "green" or "red" being affixed to that point, indicating whether the point is considered associated with navigable terrain or with an obstacle. After all data points have been processed, the pixels of the Map of Obstacles inherit colour labels from geometrically associated data points. This completes the algorithm.

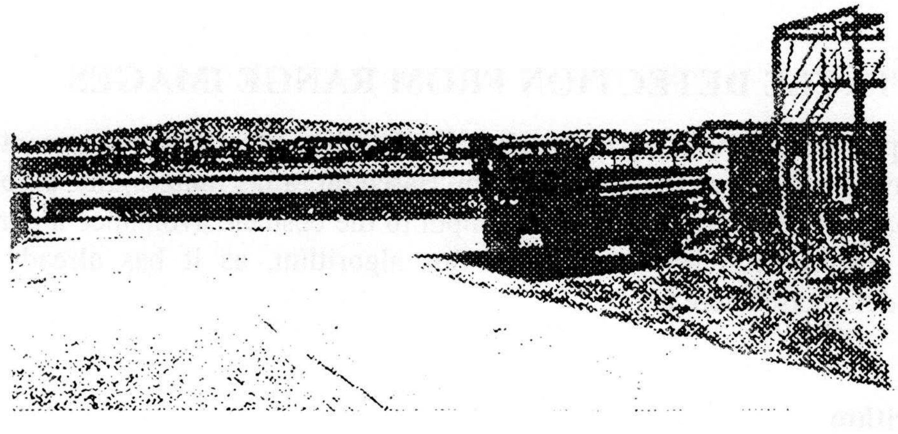

Fig. 6: Outdoor scene

An example of an outdoor scene is given in figure 6. The vehicle is driving towards a parking military truck, while crossing an air base access road.

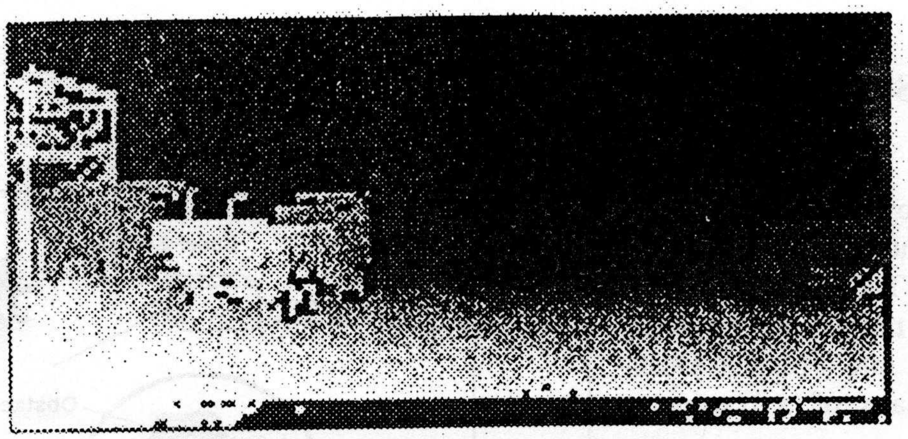

Fig. 7: Range Image (grey-scale)

Figure 7 shows a range image taken from this scene. A range interval of 0 - 50 m is mapped linearly on a grey-scale ranging from white to black. A limited number of measurement errors (drop-ins and drop-outs) are visible.

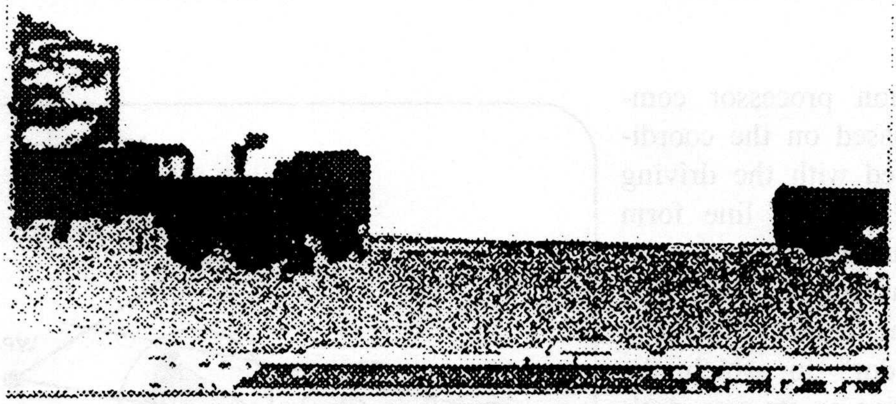

Fig. 8: Range Image (colour labelled)

Figure 8 shows how the algorithm has labelled data points in the 3-d image. The pixels in the range image have the same intensity as in the grey-scale presentation; however, a pixel giving rise to a green (grey) or red (black) 3-d image point inherits this colour. The algorithm detects all obstacles.

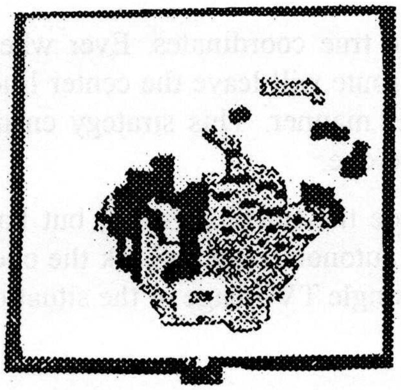

Fig. 9:Map of Obstacles

Figure 9 (left) displays the associated map of obstacles. The box at the bottom represents the sensor-carrying vehicle.

6 OBSTACLE AVOIDANCE

Fig. 11 shows the two components of the obstacle detection subsystem The Laser Scanner generates a range image which is transformed into a Map of Obstacles by means of a transputer-system.

This Map of Obstacles is used by the navigation processor as one of its two main information (data) sources. The second main information stream is originated by the dead reckoning navigation unit.

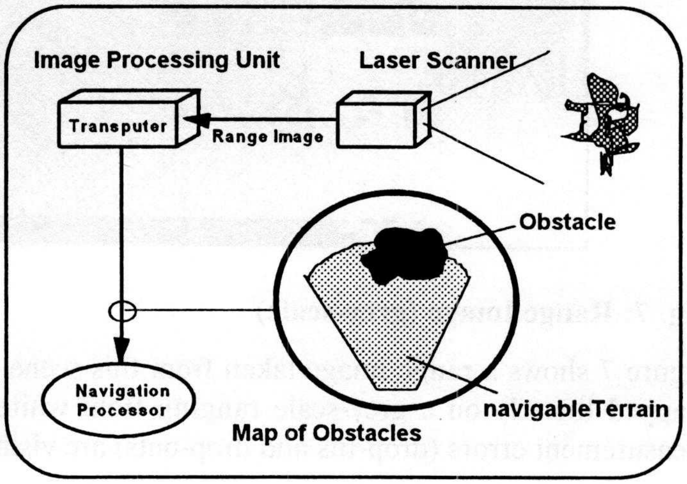

Fig. 10: Obstacle Detection System

The navigation processor computes first, based on the coordinates delivered with the driving command, a straight line form the start-point to the goal-point (or next way-point). This line represents the center line of a "travel corridor" in which the robot may drive on its own decision without operator support. (The width of the corridor may be set freely).

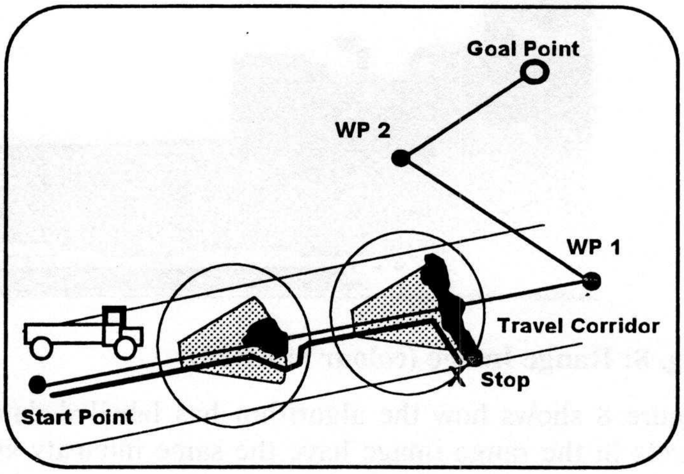

Fig. 12: Obstacle Avoidance Strategy

As maps of obstacles appears, four per second, they will be layed over the travel corridor and adjusted to the true coordinates. Ever when the center line leads into an obstacle area the driving route will leave the center line, but stay close to the obstacle area in a "rubber hand" manner. This strategy ensures a driving route as close as possible to the commanded one.

If these "roundabout ways" cannot be placed inside the travel corridor, but have to cross the border of the corridor, the robot will stop autonomously and ask the operator at the control post for help, by transmitting him a single TV-image of the situation.

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