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Design of a navigation system for automated guided vehicles operating in a man-machine shared environment

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Abstract

Automated Guided Vehicles (AGV) often share the same environment with humans. Unexpected obstacles placed in the guide path of the vehicles result in costly stoppages. The design of a modular navigation system which detects obstacles as they reflect a patterned light projected from the AGV onto the floor ahead of the vehicle is described. Distortion of the pattern sensed by a CCD camera, mounted under the front of the AGV, is processed to locate the obstacle and evasive action is taken to circumnavigate the obstruction.

1 Introduction

The first Automated Guided Vehicles (AGV) were developed in the 1950s by Barrett Electronics for use in warehouses. The early automated trucks were mainly used for towing trains of carts following a fixed wire system. This trend has continued to date where industrial AGVs follow a fixed guide path embedded in the floor or bonded to the floor surface.

The benefits brought about by automated vehicle systems include reduced labour costs since drivers are not required, reduced paper work in the form of dockets and requisitions and the fact that work need not be interrupted by rest periods. A further major advantage of automated vehicles as opposed to traditional forms of factory transport such as conveyors and railways, which require exclusive routes constructed from intrusive steel work and transport equipment, is that they allow more efficient use of the available factory space. This is made possible by the fact that AGVs use unobstructive or hidden guide-paths that are only apparent when vehicles are actually present. At other times, the thoroughfares can be used by people and other transport. This unavoidably results in interaction between the manually operated trucks and AGVs operating in the same work space simultaneously. AGVs can not operate with the same level of flexibility as manual truck drivers and require their path-guide to be completely unimpeded. Furthermore, untidily stacked pallets or crates inevitably placed in the AGV path-guide leads to the automated vehicle becoming stranded.

Considerable research and development has been carried out in an attempt to design a reliable and commercially viable system to overcome the drawbacks of wire guided AGVs. These systems are aimed at allowing the vehicle to deviate from the planned path in order to circumnavigate the obstacle placed on the AGV's path and return to its original path after clearing the obstacle. These systems either require a detailed map of the factory layout or rely on sophisticated sensors such as scanning laser range finders (Dunlay[1] and McTamaney[2]), CCD camera systems (Takeuchi[3]), ultrasound scanners(Brady[4] and Borenstein[5]) etc. These systems either employ sensitive moving parts which are not generally suitable for use in harsh industrial environments or invariably suffer from misleading reflections, rogue echoes and inevitably require a large amount of signal processing which in turn necessitate an on-board high speed computer with a large storage device. The size and cost of these systems, which usually involve replacing the AGV's existing guidance system and installing new markers and reflectors, generally inhibits their adoption in manufacturing industry.

A cost effective and practical solution to the problem of obstacle detection and avoidance is a modular system, auxiliary to the existing AGV's primary guidance which does not require major modifications. During normal operation, this system should remain transparent to the primary AGV's guidance system and temporarily take over the control of the vehicle drives until the obstacle has been successfully circumnavigated and has returned to its planned path.

This paper describes a modular obstacle detection and avoidance system which can be retrofitted to conventional AGVs with minimum modification. This system which was originally reported in 1991 by Lockwood[6], relies on a simple low cost CCD image sensor to detect the distortion to a projected coded light pattern, projected ahead of the vehicle, by an obstacle(Mehrdadi [7,8]).

2 Obstacle detection and avoidance

Light patterns with known geometrical properties are used to obtain information from illuminated scenes. This is known as structured light and is used in applications such as metrology and Computer Aided Engineering (CAE) for surface recognition. 3-D machine perception systems which use binary codes and standard cameras are used to model the surface of static objects(vuylsteke[9], and Bhatnager[10]). The real-time operations have not been possible due to excessive demand on computation and attempts to speed up the operation have not been successful. These methods rely on analysing the entire illuminated

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scenes in order to obtain the necessary information and hence the use of high speed computers and time involved in processing the data are unavoidable. Our system which utilises a vertical-bar coded pattern and processes discrete elements of the code does not impose heavy demands on computational power of a computer and hence the entire object detection and avoidance can be implemented using a single chip microcontroller.

A standard slide projector is used in the obstacle avoidance system to project a coded light pattern onto the floor ahead of the AGV. The projector is installed 1m above the floor on the AGV as shown in figure(1).

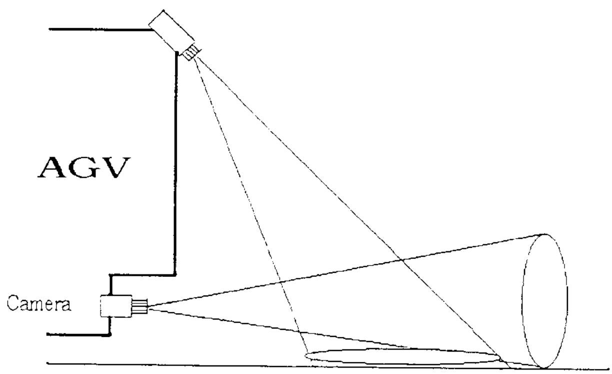

Figure (1) - Schematic diagram of the obstacle detection system

The CCD camera is mounted under the front chassis of the AGV and is pointed directly to the guide path. When a 35mm slide made of a known pattern is loaded into the slide projector, the illuminated area of the floor remains invisible to the camera under normal conditions. As the AGV moves, the illuminated zone ahead of the vehicle moves forward accordingly. However, when an obstacle appears in front of the AGV and enters the illuminated zone, the coded pattern is disturbed and is reflected back to the camera, as a whole or part depending on the size and orientation of the object. Consequently, this distortion appears to 'grow' from the floor and progresses vertically in the image. Figure(2) shows this effect which can be enhanced by virtue of the projector/camera geometric relationship. The distorted light pattern sensed by the camera is used by the on-board microcontroller to detect the position and size of the obstacle. This information is then used to control the vehicle drives to circumnavigate the obstruction.

Several masks were used in an attempt to identify the most effective structure of the projected light pattern. The most effective masks are those which project patterns that are unlikely to occur naturally. Examples of naturally occurring patterns in this context are graphics or text on packing cases etc. All the projection masks with discrete shapes such as diamonds or dots set in a predetermined grid performed well and obstacles could be reliably detected.

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However, the task of two dimensional edge detection and thresholding are too time consuming to be carried out by a microcontroller. The design was therefore simplified to reduce the processing demands whilst maintaining its reliability.

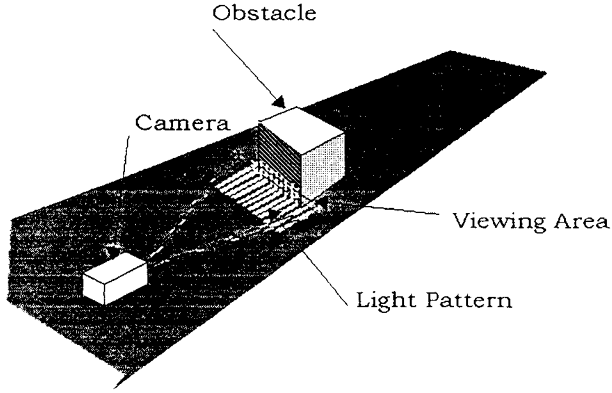

Figure (2) - Obstacles disturb the coded light pattern

In order to detect the pattern by a computer, images were digitised into a matrix of grey levels. The resulting array was pre-processed using an edge detection and thresholding algorithm. Edge detection is essentially a high-pass filtering procedure which accentuates abrupt changes in contrast in an image. Thresholding is a selection procedure used to determine which edges are accepted for image analysis and which are ignored. These processes help to eliminate the effect of disparate contrast caused by variable ambient lighting conditions and obstacle surfaces.

Vertical bar patterns can be used to reduce the image processing task from two dimensional to one, providing that objects are stood on the floor. In order to detect obstacles, the system needs to process only a narrow horizontal strip of the image which corresponds to the position where objects begin to distort the light pattern. However, uniform bar patterns may become confused with patterns occurring on objects which are not obstacles to be avoided. For example uniform markings on distant walls or packing cases, or iron railings with uniformly spaced vertical supports etc. A coded projection mask has been designed to assist in overcoming the possibility of false obstacle detection. In general, codes with a large 'information' content will result in the most reliable obstacle detection. Such a code could be realised in the form of a projection mask consisting of several differently spaced vertical bars. However, the major disadvantage of this approach, is that only large obstacles, disturbing the whole projected pattern could be reliably detected. Since the system must also be able to detect 'thin' obstacles, several discrete codes across the image must be used and a compromise between code size and video system resolution must be

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found. Several factors affect the design of a compromise light code including the aforementioned resolution of the detection system, the 'thinnest' detectable object, and the required speed of the information extraction algorithm. In order to maintain modest memory requirements and high processing speed, images are digitised with a horizontal resolution of 1:256. This results in a projected resolution of approximately 3mm at a distance of 1m with a viewing angle of 45 degrees using a 12mm camera lens.

A repetitive code similar to that shown in figure(3) was found to produce reliable results. This code horizontally divides the projection area into discrete regions. The detection of any complete code indicates the presence of an obstacle and its position in the image reveals the position of the obstacle in front of the projector and camera.

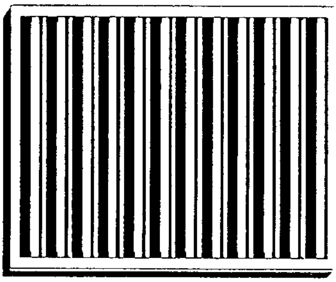

Figure (3) - Vertical bar mask

The prototype image processing software includes an algorithm which automatically identifies the features of the pattern in use. This allows various masks to be deployed without the need to specify the physical dimensions of the code.

3 Image processing of obstacles

The falling cost of CCD arrays together with their improving quality makes them eminently suitable for use in machine vision systems. The robustness of modern CCDs allows their use in systems that may be subjected to noise, vibration and other harsh environmental conditions. A low-cost monochrome CCD video camera was used as the detection element of the obstacle avoidance system. A particular feature of the 1/2" CCD array used in this design is its sensitivity, which enables the camera to operate in light levels down to 0.5 Lux. Conversely, a built in auto-iris adjusts the camera aperture according to the average light intensity falling on the CCD array to prevent saturation in bright ambient light conditions. The array consists of 370x350 light sensitive elements.

For objects to be avoided without collision, the projected light pattern must produce an image at least as wide as the automated vehicle when it is focused

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on the floor. A viewing angle of 45 degrees is required for the camera to detect the full width of such an image at a distance of approximately one meter. This is achieved by using a 12 mm wide-angle camera lens.

A central feature of the digital image processing system is to convert standard video signals generated by the camera into a form which can be processed by a computer. This is achieved by digitising the video signal and storing it in a memory array. Each picture element (pixel) has a numeric value representing the light intensity, or grey level, of the corresponding point in the video image. Each video line signal lasts for 64 micro-seconds. For a horizontal resolution of say 256 pixels in a digitised image array, the video line signals must be sampled at 250 nanosecond intervals for real-time operation.

The monochrome Video Frame Store used in the design operates in real-time with a resolution of 256x256 picture elements. Each pixel has a grey level value in the range of 0-255 and complete video images are digitised in 25 milliseconds.

4 Code recovery

The coded light pattern sensed by the CCD camera is used to detect the presence and position of the obstacle entering the illuminated zone. The signal processing required to achieve these tasks is performed in three stages;

1. pre-processing stage consisting of two digital filters to clean up the video signal
2. peak detection and feature extraction stages to isolate potential code parameters
3. code measurement and recognition stages based on 'decision theoretic' pattern recognition techniques

Digital filters are used to reduce the effect of quantisation errors which appear as a wide band noise superimposed on the digitised video signal and as a pre-processing stage to maximise the operating speed of the obstacle detection system.

The first filter consists of a non-recursive transversal filter to average eight horizontal lines of the image. The result of this filtering operation is a single line array in which each element is the average of the corresponding elements from the original horizontal lines. The effect of this operation is to enhance the influence of persistent vertical patterns in the image array whilst reducing the effect of spurious noise. The choice of the number of lines to average depends on both the minimum height of the object being detected and the required algorithm execution speed. Whilst a large number of lines results in greater enhancement of vertical patterns, if the object in the image is not tall enough to produce persistent vertical patterns, the process will fail. Conversely, if too few lines are averaged, the process has a reduced immunity to noise. Experiments

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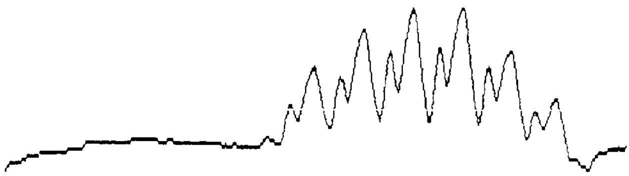
showed that eight horizontal lines of the video image provide reliable obstacle detection, combined with high execution speed. In the prototype design, this corresponds to a physical horizontal strip of approximately 20mm when projected onto an object one meter in front of the camera.

The resultant array of 256 averaged elements is further processed to remove high frequency components in the horizontal direction. This is achieved by using a recursive digital filter.

Whilst the low pass filtering stages are essential for removing high frequency noise from the digitised image array to simplify later processing, care has to be taken not to filter out important information. The nature of the code pattern being sought from the array (ideally high contrast light and dark bars), means that it has high frequency components in the abrupt changes between light and dark. If the cut off frequency of the low pass filter is excessively low, vital information may be lost. A compromise was therefore found by selecting a suitable filter time constant which produces a filtered output as shown in figure(4).

(a)



(b)

Figure (4) - a. Original video signal b. Processed video signal

The recursive filtering stage affects the range of bar codes which can be used as projection masks due to its cut off frequency characteristics. If the code period is short (high frequency), true video data will be attenuated along with the quantisation noise which the low pass filter is designed to remove. Conversely, when the code period is long, the 'thinnest' detectable object is limited. A compromise is reached in the prototype design with a code period of 16 'horizontal pixels', resulting in a thinnest detectable object of approximately 50mm.

The decision theoretic technique which operates on the time series of signals directly rather than transferring them into the frequency domain was used to extract key features of the coded light pattern. This approach is suitable in this application as only one pattern is required to be recognised. Features are

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extracted from the filtered data and transformed into 'feature space' where they are tested against predetermined code parameters. Positive test results indicate the presence of an obstacle to be avoided. In the digitised video signal, the absolute magnitude of the signal cannot be used as this varies widely depending on the nature of the object reflecting the light pattern and the ambient lighting conditions. However, code patterns which appear in the image always have the same shape as illustrated in figure(5).

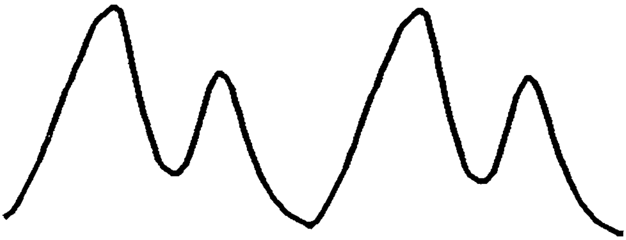

Figure (5) - Spatial relationship of maxima and minima

This general shape is obtained from the reflected light code regardless of the absolute video signal magnitude. With reference to figure(5), the features, which do not depend on the magnitude of the signal are, the presence of maxima and minima of grey levels associated with the code and the spatial relationship between them. The key features of the detected code are tested against the code parameters received from a plain board placed in front of the cameras during the initialisation stage of the operation. A decision theoretic approach has been adopted for recognising codes in the projected light pattern. If a match is detected, it is due to an obstacle entering the projection area in front of the vehicle. Subsequently, the system initiates the obstacle avoidance stage and takes suitable manoeuvres to steer the vehicle.

5 Obstacle avoidance

Most proposed obstacle avoidance systems require the absolute position of the vehicle on the map of the factory floor. Gonzales[11] and Shen[12] describe systems which record the orthogonal co-ordinates of the AGV and use this information to return the vehicles to their path after deviating to clear obstacles. The task of maintaining an accurate map of the operating environment is critical and cumulative errors can reach an unacceptable level. In our design, a local map is developed by the on-board processor only when an obstacle is detected.

In contrast with other systems, the guide path is specified as a vector rather than an orthogonally specified map. The angle of deviation and the distance the AGV travels to clear the obstruction are used to return the vehicle to its original path. When the obstacle detection system senses an obstruction in the vehicle path, two variables representing the current deviation from the path and the current heading are set to zero. As the vehicle leaves the path to avoid the

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obstacle, its relative deviation and heading are referred to this initial 'zero vector'. The deviation and heading are denoted by 'Y' and 'ϕ' respectively as shown in figure (6). The vehicle rejoins the original guide path when the deviation and heading return to their initial values. The new location is derived from Y= r.sin ϕ where 'r' is the distance travelled on a particular heading.

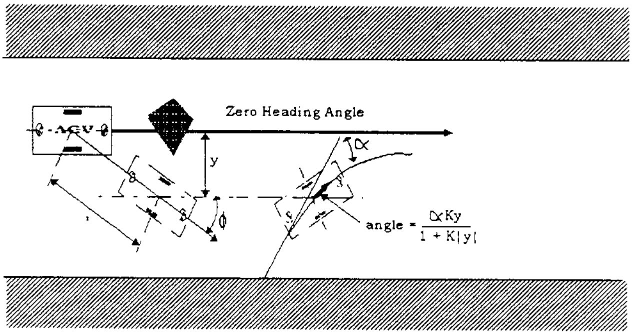

Figure (6) - AGV deviate from the guide path to clear an obstacle

When an obstruction is encountered, the vehicle turns 5 degrees to the left or to the right depending on the position of the obstruction and advances by 50mm. In general, a complete obstacle avoidance sequence is constructed from several primary 'turns' and 'advances', and may involve the avoidance of more than one obstacle. A running aggregate of headings and deviations is maintained to enable the system to return the vehicle to the guide path after circumnavigating the obstruction.

6 Conclusion

The described system was successfully tested under factory conditions with obstacles of various sizes and shapes placed in front of the AGV. The system exhibited a positional error of $\pm$ 2 cm on returning to the AGV's original path. This error is accepted in wire-guided systems which can locate the embedded wire guide-path from a distance of 10 cm. The obstacle detection response time of 0.8 seconds and the avoidance response time of 2.4 seconds as measured during tests is based on a low-cost microcontroller running at 1 MHz clock frequency. The overall response time could be considerably reduced by incorporating one of the high speed processors which are consistently introduced into the market by various manufacturers.

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References

1. Dunlay,R.T., Obstacle Avoidance Perception Processing for Autonomous Land Vehicle, Proc. of IEEE International Conference on Robotics and Automation, 1988, pp 912-917.

2. McTamaney, L.S., Mobile Robotics: Real Time Intelligent Control, IEEE Expert, 1988, pp 55-68, vol. 2, part 4.

3. Takeuchi, T. and Nagai, Y., Fuzzy Control of a Mobile Robot for Obstacle Avoidance' Information Sources, 1988, pp 231-248, vol.45, part 2.

4. Brady, M. and Durrant-Whyte, H., Sensor Based Control of AGVs, Computing and Control Engineering Journal, March 1990, pp 64-70.

5. Borenstein, J. and Koren, Y., Obstacle Avoidance with Ultrasonic Sensors, IEEE Journal of Robotics and Automation, 1988, vol.4, part 2, pp 213-218.

6. Lockwood, S., Mehrdadi, B., and Chandler, J., Design of an Obstacle Avoidance System for Automated Guided Vehicles, Proc. of 8th International Conference on Systems Engineering, 1991, pp 428-433.

7. Mehrdadi, B., Lockwood, S. and Chandler, J., Modular Obstacle Detection and Avoidance System for Automated Guided Vehicles, Proc. of 9th National Conference on Manufacturing Research, 1993.

8. Mehrdadi, B & Lockwood, S., An AGV Navigation System Using Projected Light Patterns, Proc. of 12th International Conference on Systems Science, 1995.

9. Vuylsteke, P. & Oosterlinck, A., Range Image Acquisition with a Single Binary Coded Light Pattern, IEEE Transaction on Pattern Analysis and Machine Intelligence, vol. 12, No. 2, Feb. 1990.

10. Bhatnager, D. & Pujari, A.K., Static Scene Analysis Using Structured Light, Image and Vision Computing, April 1991, vol. 9, no. 2.

11. Gonzales, R.C., & Wintz, P., Digital Image Processing, Addison-Wesley Publishing Co., 1977.

12. Shen, H.C., & Pang, G.K.H., An Intelligent Control of Roving Robots, Transaction of IEEE, 1988, pp 481-485.