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AHS用スキャニングレーザレンジファインダーの試作及びそれを用いた自律移動車の走行実験

Design of a 3D Scanning Laser Rangefinder and Its Application to Autonomous Land Vehicle

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1. Introduction

Recently, a great deal of researches on AHS (Automated Highway System) has been carried out. This program involves a series of improvements in automobiles and highways infrastructure. One topic of AHS is about AVCSS (Advanced Vehicles Control and Safety Systems) that is aimed to develop accident avoidance systems for automobiles. Current safety systems, such as air bags and improved structures, have reduced the injuries of accidents, however it is more important to prevent the accident from happening. The purpose of this study is to present an effort to reduce car crashes in highways

It is known that the main reason for car accident is the lag on the driver's reaction time caused by driver distraction, fatigue or inattention. Thus, accidents can be reduced considerably by constructing a forward looking system able to enhance the driver's perception. Moreover, to avoid accidents effectively, more than only to forewarning the inattentive driver in situations of danger, this system is also required able to lead the vehicle by a safe path.

The implementation of this forward looking equipment requires object detection, as well as highways contours detection. Object detection devices currently used in AVCSS are based on ultrasound, microwaves, laser and image processing. Each has its pros and cons according to the detection range. Ultrasonic sensors are applicable only for short range object detection. For locations beyond ultrasonic sensor's measurable range, distance measurements are achieved by sensors based on laser, microwaves or image processing.

The object detection device must be able to achieve long range measurements, especially for applications in highways. The reason is that distance between the vehicle and the obstacle must be kept enough to allow the vehicle to stop or change the trajectory in time to avoid an accident. In this study, laser was used for the long range detection.

A great diversity of situation should be considered for the application of the object detection device on highways. Thus apart from detecting objects only in a fixed direction in front of the vehicle, this system must achieve object detection within a range of an angle in front of the vehicle. For this purpose, in this study, a 3D scanning laser rangefinder was constructed to provide object detection.

With the developed 3D scanning laser rangefinder, automatic driving experiments were carried out. In the experiments an image processing method was implemented to obtain information about the contour of the highway.

In this paper, the design and the construction of a 3D scanning laser rangefinder is described. Also the results of the automatic driving experiment using data from this device and from the image processing method is reported.

2. Laser rangefinder

2.1 Optical system

For the purpose of installing the laser rangefinder in automobiles, a compact configuration of this device is needed. This compact configuration can be achieved by using an optical system where the optical axis of the emitted beam and the optical axis of the returned light are collinear, as illustrated in Fig. 1. In this configuration, the high intensity laser pulse is generated from the laser diode. The laser is collimated by the emitter lens and then deflected 90^o by the laser mirror. By this procedure the optical axis of the emitted beam becomes coaxial to the optical axis of the returned light. After the laser beam is collimated in the direction of the returned light, the laser beam is reflected by the vertical mirror. Then the laser beam reaches the horizontal mirror and is directed to the targets. The backscattered light reflected from the obstacle is also reflected by the horizontal mirror and the vertical mirror. After being reflected by the vertical mirror, the reflected light is converged to the photo diode by the receiver's lens. In front of the photo-diode, an optical filter was placed to reduce the radiation from other light sources.

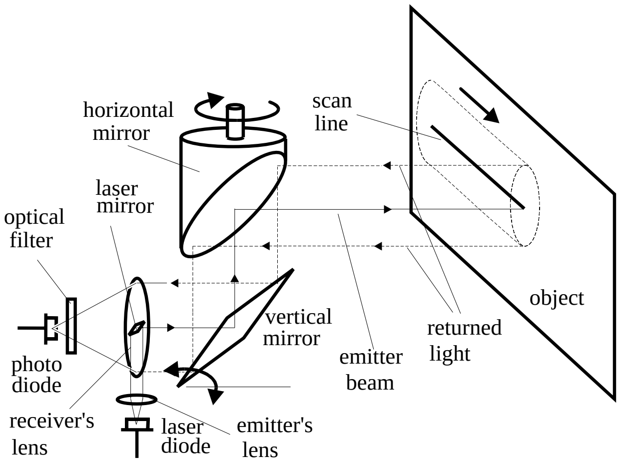

Fig. 1 Collinear configuration scanner

The vertical mirror is responsible for the vertical displacement of the scan line. The rotating motion of this mirror deflects the laser beam in the horizontal direction, generating a horizontal scan line. The 3D scanning is obtained by sweeping the laser beam at high velocity in the horizontal direction and at the same time sweeping the vertical direction in a much slower velocity.

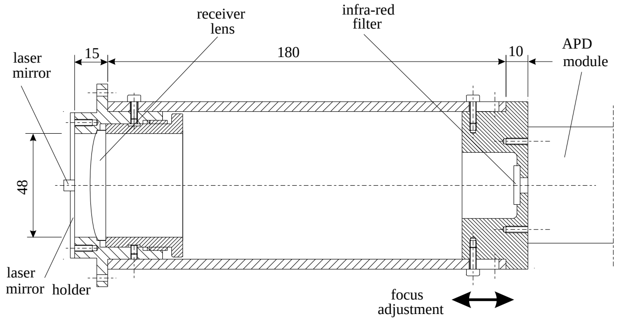

Fig. 2 Laser rangefinder set-up.

The use of this configuration requires special attention for the fact that optical efficiency of the receiver's system is reduced by placing the *laser mirror* in front of the receiver's lens. Thus, the dimension of the *laser mirror* must be minimized as much as possible. The mechanical set-up constructed for obtaining the collinear optical axis configuration is shown in Fig. 2. At present, the laser beam dimension was set at $\phi 5mm$, while the diameter of receiver lens is $\phi 50mm$. Another important procedure worth to be noted is the procedure for placing the laser mirror. This placement must be done with care to avoid reflections by the edge of this mirror from falling into the receiver's optics.

The direction of the emitted beam optical axis was adjusted by positioning the laser mirror. For the sake of mechanical simplicity, this adjustment was done manually by plastic deformation of the laser mirror holder. Even though this calibration procedure is time consuming, the advantage of obtaining a compact system justifies the choice.

2.2 Scanning mechanism

Considering the use of the 3D scanning laser rangefinder in a great diversity of situations, the horizontal angular range is defined as 120^o, and the vertical range varies from the ground at 20m until 1.5m height at 100m far, as illustrated in Fig. 3.

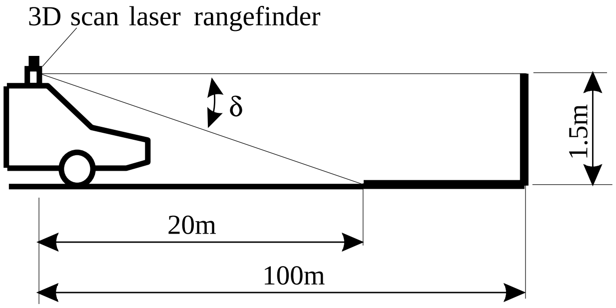

Fig. 3 Vertical view angle of the scanner laser rangefinder

Usually, polygon mirrors are used to implement scan mechanisms. But, in order to avoid loss of optical efficiency between the receiver's lens and the scanning mirrors, these mirrors must have at least the same size as that of the receiver's lens. Thus, the use of polygon mirrors in the present case will result in an oversized scan mechanism. The solution that avoids the loss of optical efficiency and keeps the scanner mechanism compact is the use of a mirror mounted on a 45^o tilted cylinder.

The inconvenience of using the tilted cone configuration is the fact that the asymmetric geometry of this solid causes problems of vibration on the scanning mechanism. After balancing the mirror base, a test was executed. At this test, rotations of about 2000rmp were obtained only with a small level vibration in the scanning mechanism. The motion of the horizontal mirror is controlled by a servomotor SANYO R404. The encoder coupled to this motor axis has a count of 2000 pulses per revolution. Thus, the horizontal scanning resolution is 0.18^o. In order words, for measurements at the maximum distance ($100m$), the interval between two consecutive measurements is $0.3m$.

The vertical sweep of the laser beam is given by the continuous movement in small amplitude of the vertical mirror. This movement is not convenient to be executed by coupling the vertical mirror directly to the motor axis. The solution employed was to use a four bar mechanism to convert the continuous rotational movement of the vertical mirror's servo-motor (SANYO R302) into a small amplitude repetitive motion.

2.3 Electronic system

In Fig. 4 is shown the block diagram of the laser rangefinder and the interface of the laser rangefinder to the computer. The interface is done by a *PIO (Parallel Input Output) board, a D/A (Digital to Analog) converter board* and a *the counter board*. All of these extension boards are connected to the computer bus. A timer is used to measure the elapsed time between the emission and the reception of the laser pulse. An $100MHz$ oscillator generates the base clock for the time measurement. The output of the timer is fed into the computer through the PIO for distance estimation. The PIO also controls the emission of the laser pulse. The D/A extension board provides a reference voltage to the *motor drivers*for the velocity control of the *motors*. *Motor A* and *motor B* move the horizontal and vertical scan mirrors respectively. The counter extension board feeds the computer with data about the angular position of the *encoders A* and *B*. *Encoders A* and *B* are 2000 steps/rev encoders coupled to the motors axis.

2.3.1 Emitter and receiver

A semiconductor laser diode (LD), HAMAMATSU L7055-04, is used as the laser source of the emitter. The wavelength of this laser is $870nm$.

The laser is driven by a circuit that provides pulses of 12A current at a duration of 20ns. The pulse emission is commanded by the rising slope of the *emitter clock*. Due to limitations of the LD the maximum frequency for the *emitter clock* is 35kHz. Based on the LD data sheet, at the conditions described above, an optical output of about $20W$ is obtained.

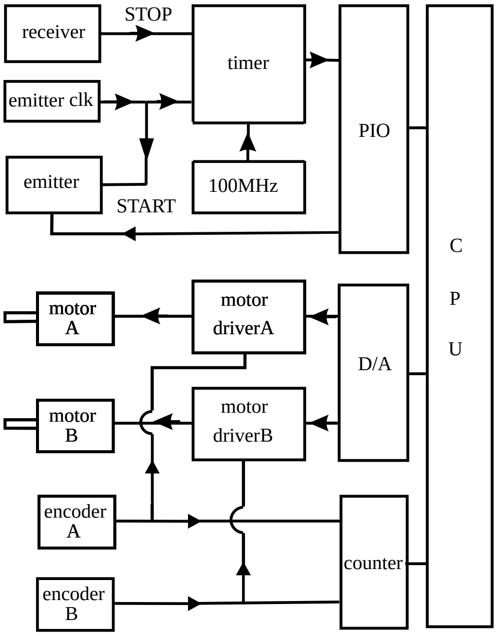

Fig. 4 Electric/electronic block diagram of the scan laser rangefinder.

For the detection of the low intensity reflected light, an avalanche photo-diode (APD) was used. The first stage of amplification of the returned light signal is done in a commercially available APD module (HAMAMATSU, C5331-02). Since the amplitude of this signal is still too low to be dealt with by the timer circuit, a high speed amplifier has been also constructed.

2.4 Control software

The flow chart of the software used for the scan laser rangefinder control is shown in Fig. 5. The initialization stage consists of initializing the extension boards and turning on the scanning motors.

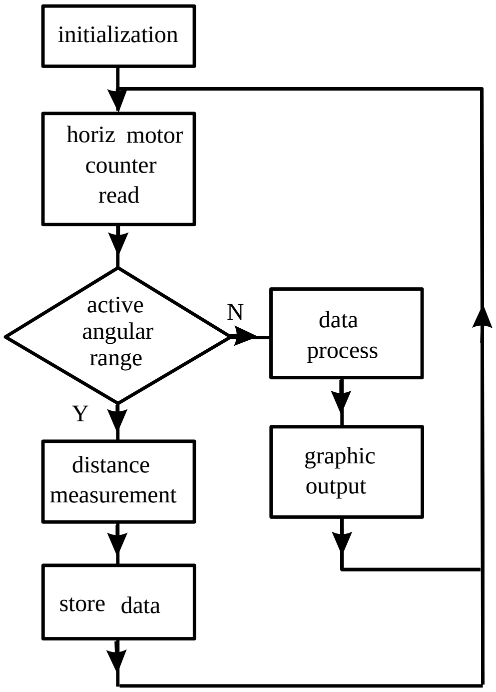

Fig. 5 Control software flow chart.

After the initialization, the horizontal motor position is read. If the position of the horizontal mirror is within the horizontal angular range (120^o), the distance measurement process starts. For each position of the horizontal mirror, many distance measurements are taken and stored. This process continues until the position of the horizontal mirror falls out of the horizontal angular range. At this moment, the laser beam emission is suppressed and the acquired data starts to be processed.

The data processing consists of filtering and averaging the data obtained from each position of the horizontal mirror along the horizontal angular range. When the scanning velocity is not very high, more than one data can be obtained one position of the horizontal mirror. If any data taken from the same position of the horizontal mirror presents a value beyond a variance limit, this data is automatically eliminated by the filtering procedure. After the filtering procedure, the average distance for the present position is calculated.

The average distance for each position of the horizontal mirror are presented on a polar graph on the computer screen.

3. Distance measurement

3.1 Distance measurement using time-of-flight

This method consists of measuring the elapsed time of a laser pulse from its emission to its reception after having been reflected by an object. Then, the distance measurement is obtained by eq. (1).

$$d = \frac{c\Delta t}{2} \tag{1}$$

Where:

d : distance from the laser rangefinder to the object

Δt : time taken from the emission to reception of the laser pulse

c : Light velocity $c = 3 \times 10^8$ [m/s]

Fig. 6 illustrates the signals from the emitter, the receiver and the reference threshold voltage. To measure the elapsed time between the emission and the detection of the laser pulse, at first, a good reference is needed to indicate the time of emission of the laser pulse and the time of the reception of the light.

The distance measure process starts with the emission of a short duration high power laser pulse. Since the laser pulse is emitted when the rise slope of the *emitter signal* is detected, the rising slope of this signal starts the time counting process. This process continues until the detection of the pulse in the receiver's signal. The time when the receiver's signal crosses the threshold voltage is not a good

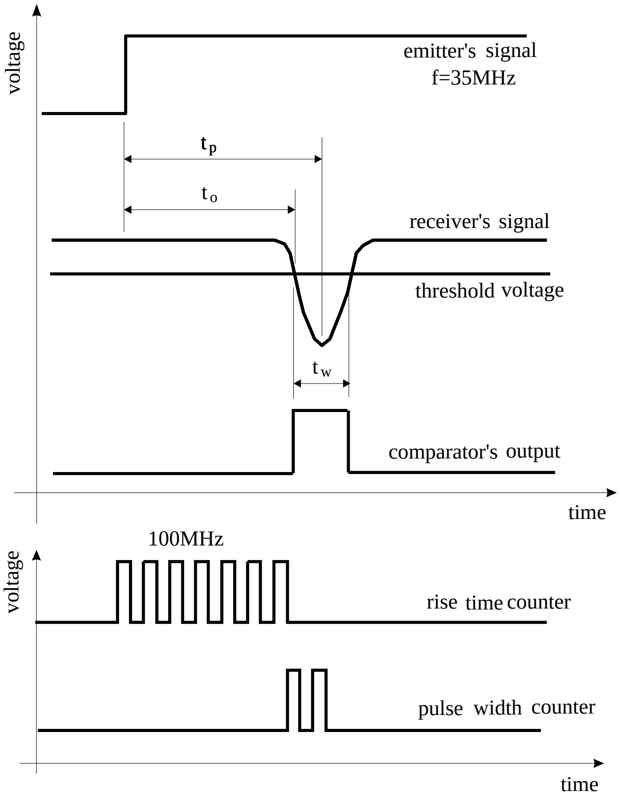

Fig. 6 Distance measurements by time-of-flight method.

reference for the time of the reception of the light. The reason is that the time when the fall slope crosses the threshold level varies according to the intensity of the returned signal. Since the pulse in the receiver's signal is almost symmetric, the position of the peak can be considered a good reference to indicate the arrival of the returned radiation. By assuming that the pulse of the receiver's signal is always symmetric, the signal peak is located half way between the points where the rise slope and the fall slope of the waveform cross the threshold level. With this method, the precision of the peak position is maintained independently of the peak intensity.

Thus, the elapsed time from the laser emission to the laser arrival is given by eq. (2).

$$t_p = t_o + \frac{t_w}{2} \qquad (2)$$

Where:

t_p: Elapsed time from the rising slope of the emitter signal to the peak of the receiver's signal

t_o: Elapsed time from the rising slope of the emitter signal to the moment of receiver's signal down crossing the reference threshold

t_w: Pulse width measured at threshold voltage level.

3.2 Time counting circuit

The determination of the times t_o and t_w is done by a circuit based on a high speed comparator (MAXIM, MAX961). This circuit compares the voltage levels between the signal from the receiver and the constant reference threshold voltage. The output of this circuit is a rectangular pulse starting at t_o with duration t_w. As illustrated in Fig. 6. Thus, the output of this circuit gives the position and the width of the receiver's pulse is determined.

The time counting of the elapsed times t_o and t_w are based on the quantity of pulses generated by a $100MHz$ crystal oscillator during the time interval t_o and t_w. The output from the timer consists of the quantity of pulses corresponding to t_o, half of the quantity of pulses corresponding to t_w and the quantity of pulses corresponding to the delay of the electronic components. Considering the delay due to the electronic circuit being constant, the correct value of the elapsed time t_p can be easily achieved during the computational process.

The quantity of pulses counted by the timer is fed to the computer by a PIO (parallel input out-

Fig. 7 Laser rangefinder installed on the ALV.

put) extension board, ADTEC model AB98-04A connected to the computer.

4. Scanning experiments

Upon completion, to execute the scanning experiment, the scan laser rangefinder mechanism was installed in an autonomous land vehicle (ALV), as shown in Fig 7. The ALV is an automobile that has already been equipped with the sensors and actuators needed to support computer-controlled car motion.

The result of a scan experiment using only the horizontal scanning movement is shown in Fig. 8. For ease of understanding, the map of the surrounding where the experiment was held is shown overlapped with the scan data. From these results, it can be concluded that a good approximation of the surroundings' shape can be obtained.

At the same location where the 2D scanning experiment was carried out, a 3D scanning experiment was also done. The 3D scanning experiment was done by using simultaneously the horizontal and the vertical sweep motion. The 3D scan map resulted from this experiment is shown in Fig. 9. For ease of understanding, only the left part of the experiment scenario is illustrated, as well as the scanning result.

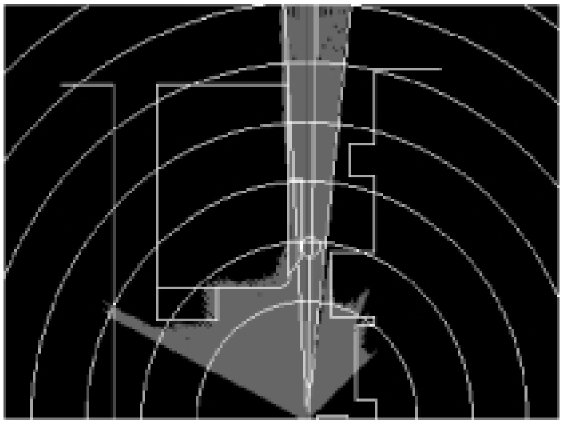

Fig. 8 Screen of the rangefinder control program showing a 2D scan map.

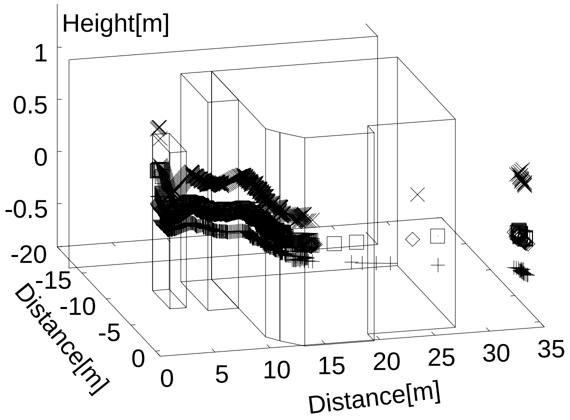

Fig. 9 3D scan map.

The next experiment was about the use of the laser rangefinder for the confirmation of clearance on the vehicle path. The trajectory for the car motion in this experiment must be planned within limiting boundaries drawn on the ground. In this experiment, the ALV trajectory is planed based on these lines. The existence of clearance along the path is checked by the laser rangefinder along the trajectory. In case the path is free of obstacle, the ALV continues its motion according to a given trajectory. In case of existence of obstacle constraining the ALV path the breaks are automatically activated and remains active until the obstacle is removed.

In order to execute this experiment, a CCD camera was installed to the ALV and the ALV motion control was done. The explanations about these topics are given in the following sections.

5. Motion control

To execute autonomous driving, the information about obstacle position, vehicle present position and the vehicle destination must be fed into the *motion control computer*. In this computer, data about the steering position, vehicle orientation and obstacle distance are read. Based on these data, the ALV trajectory is planned, and the steering position and the brakes are controlled.

To move the ALV, at first, a trajectory must be defined. In order to obtain a smooth motion of the steering wheel and assuming the initial and final conditions of the vehicle as:

- Initial orientation : 0^o;
- Final orientation : 0^o;
- Initial position : $x_o = y_o = 0$;
- Target position : x_f, y_f.

The trajectory for the car motion was defined to be a curve based on trigonometric functions, such as eq. (3).

$$x = \frac{x_f}{y_f}[y - \frac{y_f}{2\pi} sin(\frac{2\pi}{y_f} y)] \tag{3}$$

Where:

x, y : Car present position [m];

x_f, y_f : Car final position (target position) [m].

6. Image processing

For a real situation on highways, even after obstacles have been detected, the possible trajectory for the vehicle passage is still constrained by the highway lateral boundaries. In order to define a trajectory within the highway boundaries, an image processing method able to provide the relative position of the boundaries of the highway to our vehicle must be implemented. In our present study an image process method was included for the sake of executing the clearance confirmation experiment.

The present image processing method tracks the white stripes on the highway. After locating the position of the white stripes on the CCD camera's monitor, the relative position of these stripes to the ALV is determined. Since the actual distance of the point corresponding to the center of the monitor screen can be easily determined, as shown in Fig. 10, the distances of the others points in the image shown on the screen can also be determined by using basic geometry. In Fig. 11 is shown an example of the output of the matching program screen. This output is the result of a test done by feeding the matching program with recorded images of a highway.

After confirming the usage of the matching procedure, the image processing method was included to the ALV sensing system to execute the experiment with the laser rangefinder.

For the present experiment, the position of the target point (x_f, y_f) is determined by the matching program. This position is determined using the coordinates of the left and right matching rectangles accordingly to the following conditions.

If both rectangles are matched:

$$x_f = \frac{x_{left} + x_{right}}{2}$$

$$y_f = \frac{y_{left} + y_{right}}{2}$$

In case only one rectangle is matched, the program considers the width of the road as being 3m

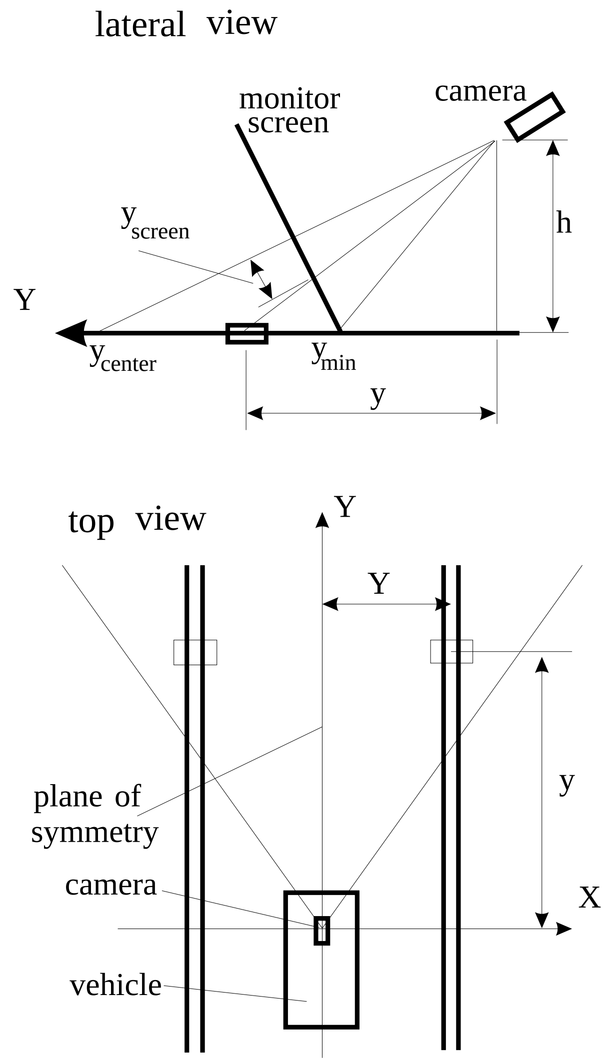

Fig. 10 Geometry of the distance determination by the CCD camera.

Fig. 11 Monitor screen showing the track of the left rectangles.

and direct the ALV to half of the road width that is, 1.5m far from the matched rectangle.

If only the left rectangle is matched:

$$x_f = x_{left} + 1.5$$

$$y_f = y_{left}$$

If only the right rectangle is matched:

$$x_f = x_{right} - 1.5$$

$$y_f = y_{right}$$

7. Experiments

The objective of this experiment is to drive the vehicle automatically based on the guidance line (Fig. 12) drawn on the ground and at the same time the laser rangefinder checks constantly the existence of obstacle in front of the vehicle.

After the target position has been fed by the *image processing computer*, the trajectory is generated by the *motion control computer*. As shown in Fig. 12, a clearance of at least 1.5m on each side of the planned trajectory was considered necessary for the vehicle transit. In this figure is also shown the map of the surroundings where the experiment was held, the scan map generated when the ALV was located at the origin of the coordinates, and the path executed by the ALV during the experiment.

At the experiment, the ALV moved along the trajectory generated based on the guidance line. The *rangefinder control computer* checked the presence of obstacles within the clearance reserved for the vehicle passage. At cases when the path was free of obstacle, the ALV continued its motion. As shown in Fig. 12 the breaks were activated at the position $Y = 10m$ due to the presence of the wall constraining the car transit.

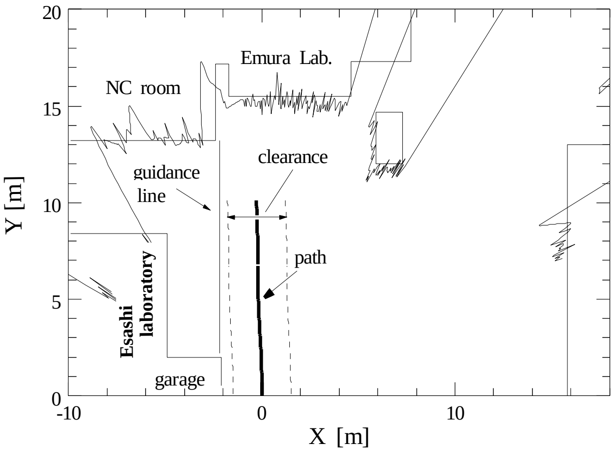

Fig. 12 Clearance for the vehicle passage.

8. Conclusions

The development of present laser radar rangefinder has accomplished its objective of locating obstacles in front of the vehicle by making a 3D map of the surroundings. And the automatic driving experiment done with the ALV of the Mechatronics laboratory, confirmed the practical use of the system.

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