Autonomous Control of Mobile Robots
— An Approach to an Orienteering Robot —

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Abstract: This paper describes the latest achievements of the research of automonous control of mobile robots carried out at the Mechanical Engineering Laboratory. The functions required of the mobile robot are: navigation using the environment model, obstacle detection, and rough road negotiation, which are just those required of a human orienteering runner. To materialize the functions in a wheeled mobile robot, we conducted the research using an environment map and a robot with ultrasonic and laser sensors, an optical object scanner, and a four-wheeled robot with active suspensions. Combining these technologies, we hope to realize an orienteering robot.

Key Words: Autonomous Control, Wheeled Robot, Orienteering Robot, Navigation, Environment Map, Active Suspension.

1. INTRODUCTION

Conventional mobile robots are mainly used in factories and hospitals where the environment of the robot is well defined in advance. Particularly for efficient locomotion on flat level floors, wheeled robots are frequently used which track continuous marks or cables laid out on the floors.

The recent demands for the mobile robots are their use in rough terrain, such as forests, farms, disaster areas, and construction areas, where the environment of the robot is defined only vaguely. Sticking in this case to a wheeled robot favouring its efficient locomotion on a flat ground, we require following capabilities of a wheeled mobile robot.

The task of the mobile robot is to move autonomously in an environment without prior experience.

(1) The robot is given a map, i.e., structured information of the environment. The robot first plans its path to the given destination on the map, and then follows the path as it senses the environment using sensors, compares the acquired information to the map, and estimates its location in the map.

(2) If there is an obstacle in the way, the robot detects it and avoids the collision with it by detouring from the predetermined path.

(3) The robot runs over uneven grounds and at the same time suppresses the shake and vibration of its body for the safety of the payload and for the stability of the environment sensors.

The capabilities look like those required of a human who enjoys the sports of orienteering. To materialize them in a robot is the image of our research.

A lot of studies have been made worldwide of the element technologies and systematization for such robots. Among them are NAVLAB at Carnegie-Mellon University Robotics Institute [1] and DARPA ALV at Martin Marrietta Denver Aerospace [2] for visual navigation including road following, and Yamabico at the University of Tsukuba for model based navigation with obstacle avoidance [3]. Also in the area of wheeled vehicles for uneven grounds, a pneumatic active suspension for a racing car at Lotus [4] and a hillside tractor for forestry use at the Forestry and Forest Products Research Institute [5].

Our research of automonous control of mobile robots was conducted at the Mechanical Engineering Laboratory as part of the Large Scale National Project of Advanced Robot Technology promoted by the Ministry of International Trade and Industry.

The concept of our research is shown in Fig. 1. We carried out the research under three subthemes: (1) Navigation using the environment model, (2) Obstacle detection, and (3) Rough road negotiation. The results of the research will be described in the following chapters.

2. NAVIGATION USING THE ENVIRONMENT MODEL

An autonomous navigation control system of a mobile robot using an environment model was built and experimented.

2.1 Map Making and Path Planning

The mobile robot is given the model or the map of the environment where it is about to move as a priori knowledge. The map should represent the geometry of the free space where the robot is allowed to pass, distinguish it from the obstructed space, and contain the information of the landmarks, which are the targets the robot can recognize using its environment sensors. The map also has to be a kind of a database the robot can refer to easily.

In our study we assume the robot environment is a building floor and have made the map in two-dimensional representation. The free space is decomposed into connecting quadrangles. A side of a quadrangle which is not shared with another quadrangle is a border of the free space, and some of the border sides are walls. Walls and wall edges are registered as landmarks. The centers of the quadrangles and the centers of the shared sides are registered as candidate subgoals for path planning.

In planning the path, possible sequences of subgoals are considered starting with the subgoal nearest the present robot position and ending with the one nearest the given destination. Among them an optimum sequence is selected as the path based on the criteria such as the minimum total distance.

2.2 Experimental System

Mobile robot

The mobile robot used in the experiment, shown in Fig. 2, is a tricycle with two independent driving wheels on the right and left and an active caster with controllable wheel direction in the rear to keep the robot stably upright. The driving wheels are driven by DC servo motors with harmonic gear reduction. The rotation of each driving wheel is detected by a rotary encoder with a resolution of 1/20000 of a revolution.

The robot has external sensors to sense the environment, namely four ultrasonic range sensors and a laser range sensor. Three of the ultrasonic sensors are mounted on the front, right and left sides of the robot. The remaining ultrasonic sensor and the laser sensor are mounted on a rotary head placed on the upper deck of the robot whose direction is servo controlled.

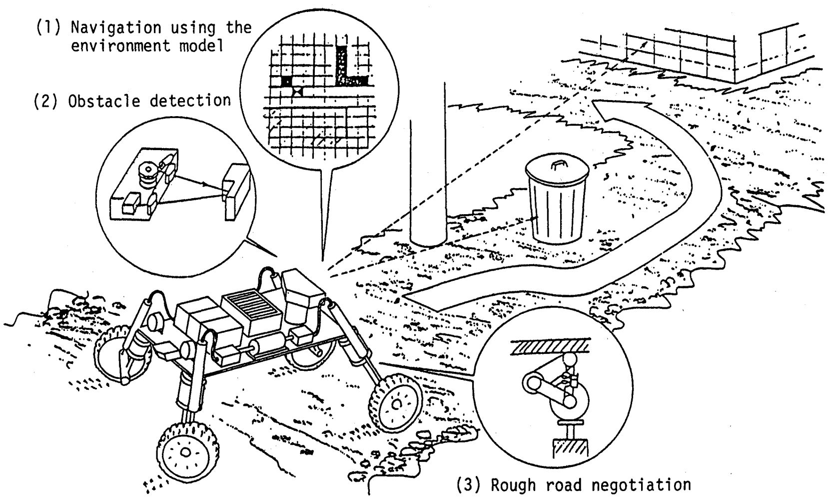

Fig. 1 Concept of autonomous control of a mobile robot.

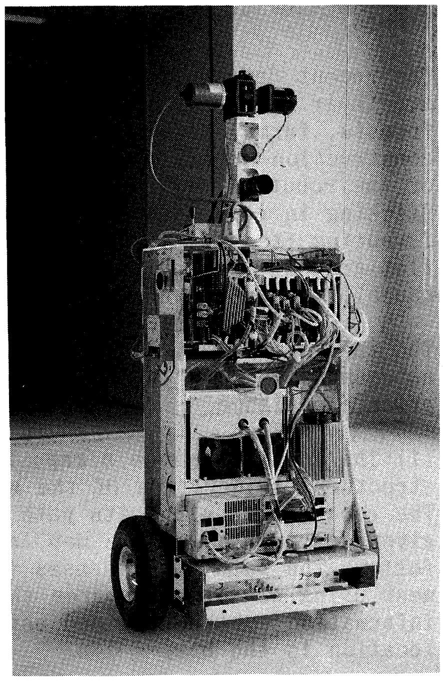

Fig. 2 Mobile robot "MELBOY".

The ultrasonic sensors can detect the distance to a wall facing nearly right with an accuracy of about 3 mm. The laser sensor has a laser emitting diode whose tilt is controllable and a CCD camera sensor to detect the beam spot made on the object surface. As the tilt is servoed so that the spot image comes in the center of the CCD, the distance to the object is calculated from the tilt by triangulation.

The computer on board the robot is a combination of CPU 80286 and NDP 80287 and performs tasks such as monitoring the robot hardware status, controlling actuators, sampling environment information, using external sensors, interpreting and executing command given by the host computer, and logging data.

Host computer
The host computer, a combination of CPU 80386 and NDP 80387, performs the overall control of the total system and interfaces the system with the operator. It communicates with the on-board computer via a wireless modem.

The software of the host computer is the main body of the total control system and consists of three parts.
(1) The man-machine interface part displays the status of the robot and the host computer and accepts commands from the operator. It also displays the environment model at the path planning and the estimated robot position and the results of the sensor information processing during the run. (2) The data management part performs maintenance of the environment model, logs the moving process data, and communicates with the mobile robot.
(3) The motion planning part, the essential part of the autonomous control, plans the path and actions of the robot, if necessary according to the operator's commands, and make commands to the robot.

2.3 Navigation Control
Position estimation
The robot position is recognized mainly based on the dead reckoning using the wheel rotations detected by the encoders. In this method the estimation error accumulates, so it should be cancelled by recognizing landmarks using environment sensors and referring them to the map. In the experiment, two kinds of landmarks are used: walls and wall edges.

The robot recognizes the wall position by measuring the distances to a wall with the ultrasonic sensor as it proceeds, and compares the measured result with the wall information registered in the map. If their difference is smaller than the predetermined value, the estimation of current robot position is corrected in the direction perpendicular to the wall. Fig. 3 shows the recognition of the wall using the ultrasonic sensor in a preliminary experiment of avoiding the collision with the wall.

The robot recognizes the wall edge using the laser sensor as it stops where it gets in the range of the target edge. The laser sensor scans horizontally by servoing the rotary head and series of range measurements are sampled for the both sides of the wall edge. The position and the direction of the edge relative to the robot, as well as the angle of the edge, are calculated using the data.

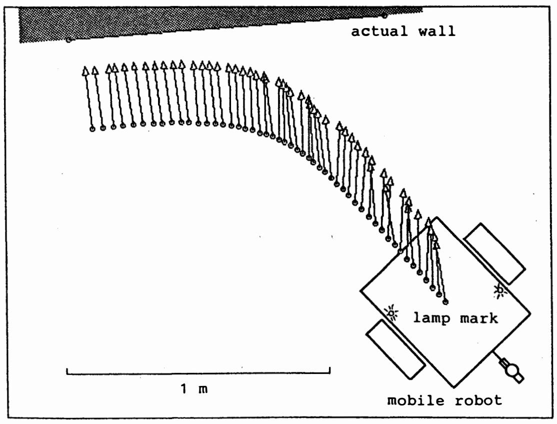

Fig. 3 Recognition of the wall using the ultrasonic range sensor.

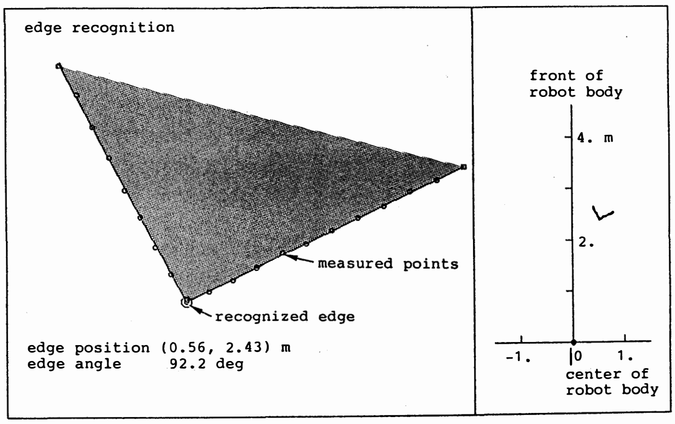

Fig. 4 Recognition of the wall edge using the laser range sensor.

If there is a good coincidence between the calculation result and the map information, the estimation of the robot position is corrected. Fig. 4 shows an example of the recognition of a wall edge using the laser sensor.

Trajectory control
For the trajectory control of the robot, we have adopted the method in which the speeds of the both driving wheels are controlled so that the velocity vector of the robot aims at the next subgoal. When the estimation of the robot position is corrected, the velocity vector is modified accordingly to lead the robot onto the correct path. At the start of the move, the robot is told its exact position. Fig. 5 shows part of the environment map used in the experiment and the trajectory of the estimated robot position.

2.4 Experimental System of a Mobile Robot Using the Virtual Environment

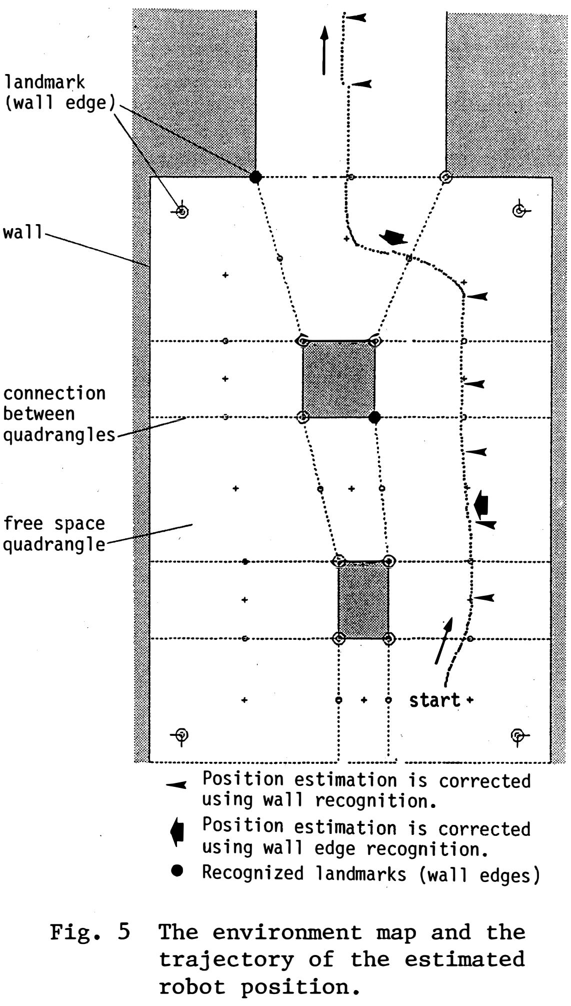

Fig. 5 The environment map and the trajectory of the estimated robot position.

The computer program for the autonomous control of a mobile robot must process the information acquired by internal and external sensors appropriately to decide the movement actions. To complete the program requires thorough tests or debugging to drive out errors. To test the program using the real robot in the real environment accompanies danger of a collision between the robot and the object in the environment. Testing it by means of software simulation is a possible way to avoid the danger, but it still remains risky just to transfer the simulation result to the reality. So we propose, as the intermediate step, the experimental system of a mobile robot using the virtual environment in which the real robot is controlled in a simulated environment[6]. Fig. 6 shows the concept of the system.

In this experimental system, the position and the movement of the robot are measured from outside and located in the virtual environment. The sensor signals the robot would acquire if the virtual environment were real are simulated and given to the robot. The robot works based on these signals using the same control logics as in the real environment. We expect in this method the danger of collision is minimized and extensive debugging is attained.

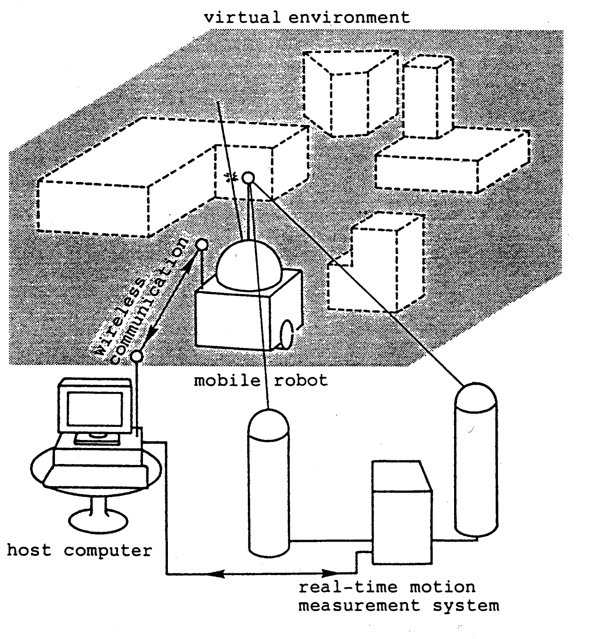

Fig. 6 Concept of the experimental system of autonomous control of a mobile robot using the virtual environment.

3. OBSTACLE DETECTION

When obstacles are anticipated on the planned path of a mobile robot, the robot should detect them with certainty using a sensor and avoid the collision with them. The sensor must comply with real time processing to allow the high-speed robot movement. We fabricated and tested an optical object scanner to satisfy these conditions.

3.1 Optical Object Scanner

The scheme of the scanner is shown in Fig. 7. As the projecting galvanomirror A and the detecting galvanomirror B are rotated with a constant angular difference, the angle between the projected and the detected beams θ is kept constant, i.e., the trajectory of the intersection of the two beams is the arc C. If the object surface is on the arc C, the reflected light is detected by the detector. Since the arc C is constant, the object position is obtained one to one if the angle α or β is measured.

As the robot equipped with this scanner proceeds, the obstacle is detected when the detection arc C comes on it. Memorizing its position, the robot plans the avoidance action.

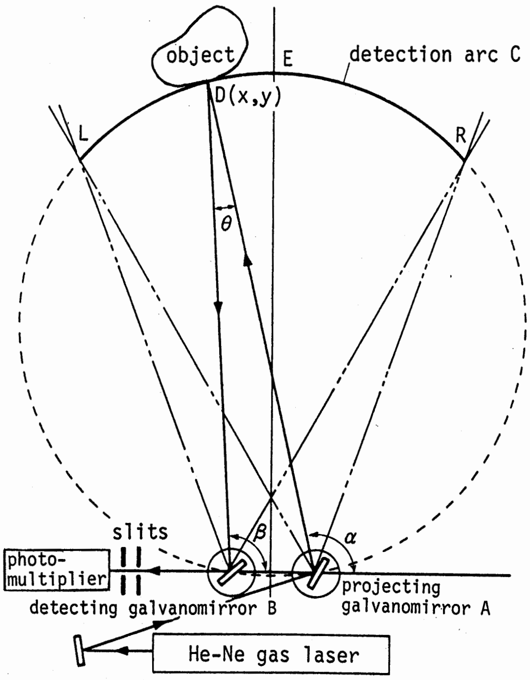

Fig. 7 Optical object scanner.

Scanning with different values for the angle θ gives different detection arcs, to detect objects nearer or farther from the base line.

The scanner has a 35 mW He-Ne gas laser as the light source and a photomultiplier as the detector. The scanning frequency is 50 Hz. Suppose the robot can proceed 0.1 m for a scan without missing the obstacle, its speed can be as high as 5 m/s or 18 km/h.

For the computer processing of obstacle recognition, an interface was made using a DMA A/D converter. As the two signals from the photomultiplier and the galvanomirror position sensor are the required input, measurement of 1000 points is possible during a scan.

3.2 Detection Test

In the test of the detection characteristics by the scanner, the scanner was adjusted with the base line 500 mm, the interval between slits 150 mm, the aperture width of slits 1 mm, and the detection arc 3 m from the base line. For the characteristics in the circumferential direction, a piece of paper with 10 cm intervals of black and white was placed along the arc. The experiment using the paper proved a good circumferential resolution as shown in Fig. 8. For the characteristics in the depth direction, a piece of paper was placed on the arc center E and every 5 cm inside and outside up to 25 cm. As shown in Fig. 9, if the object is 10 cm offset from the arc, it is no longer detected.

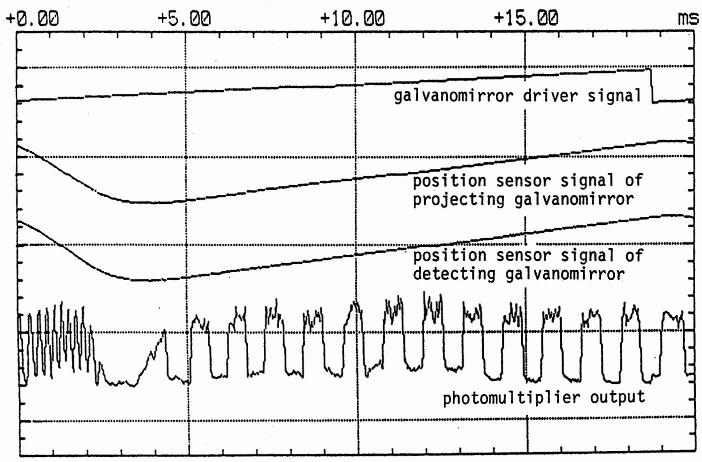

Fig. 8 Scanner output for a black and white object.

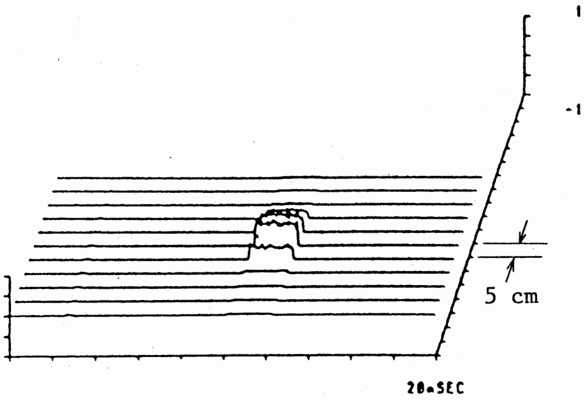

Fig. 9 Scanner output for objects at different depths.

To eliminate the influence of the reflection levels of the obstacle surfaces and the ambient light over the recognition of the obstacle, an algorithm was devised to decide the threshold level from the population distribution of the photomultiplier signal levels.

4. ROUGH ROAD NEGOTIATION

To enable a wheeled vehicle to overcome uneven grounds, the idea has been proposed of an active suspension which produces controlled force between the body and the wheel axle by means of an actuator. An active suspension is expected to play two kinds of roles: (1) to minimize the displacement and vibration of the vehicle body caused by the ground unevenness and (2) to enable the vehicle to pass over greater unevenness. In this report, however, we will concentrate on the first role of the active suspension[7][8].

4.1 Four-Wheeled Robot with Active Suspensions

We built a four-wheeled robot with an independent active suspension for each wheel as shown in Fig. 10, wheelbase 800 mm and tread 540 mm. The suspension consists of a Chebyshev approximate straight line link mechanism plus a coil spring and a direct drive DC servo motor. The stroke of the suspension is 240 mm. The stiffness of the spring is 480 N/m. The maximum output torque of the motor is 6.8 N.m, producing a force of 85 N. The vehicle has an electric steering mechanism on each front wheel and an electric driving mechanism on each rear wheel. The total mass of the vehicle is 110 kg, sprung mass 75 kg and unsprung mass 35 kg.

The robot has sensors: four potentiometers for detecting the suspension displacements, two servo inclinometers for the body attitude, three rate gyroscopes for the body angular velocity, and three servo accelerometers for the body acceleration.

The control computer PC-9801vx with 80286 and 80287 processors reads all the sensor signals and can current control the suspension motors independently.

4.2 Control

With the four-wheeled robot, the body attitude in the pitch and the roll directions as well as the body height should be controlled. Among these three variables, we started with the two variables of the body attitude.

Attitude estimation

The state of the robot, that is the attitude of the body in this case, has to be detected. We preferred the use of internal or inertial sensors to the external sensors, so that the robot need not look outside. We used servo inclinometers and vibration type rate gyros.

We tried using the inclinometer output directly as the attitude of the robot body, or the first order integral of the rate gyro output. We found neither methods very successful, for the inclinometer gave false ripples when the body swung and the gyro integral would drift easily.

The combination of the inclinometer signal and the gyro integral was investigated to produce a better estimate of the body attitude. The method is to give a greater weight to the inclinometer signal in the lower frequency domain and to the gyro integral in the higher frequency domain. We used a simple filter to function this method.

PID control

We adopted PID control for the suspension control to regulate the attitude of the robot body to be constant against the disturbance given to the wheels. We implemented the control using a computer control system. In the control system, the estimated attitude value is used for P control. Its accumulative sum was used for I control with the precaution against the windup. The rate gyro signal was directly used for D control.

The block diagram of the PID control with the attitude estimation is shown in Fig. 11. It was implememted digitally. The control cycle was 30 ms. The PID gains were determined empirically, that is, they were taken greatest as far as no serious vibration occurred in the system.

Two-axis control

For the control of the pitch and roll attitude of the robot body, we used two sets of attitude estimation filters each using an inclinometer and a rate gyro. Assuming the vehicle to be symmetric longitudinally and laterally, we denote the wheelbase 2L and the tread 2W. The attitude angles in the pitch and the roll directions are θ and ϕ. The heights of the suspension bases of the front-left, front-right, rear-left and rear-right wheels as compared with the height of the body center are h_1, h_2, h_3, h_4, respectively. Then, assuming that the absolute values of θ and ϕ are small, we get the following relations.

$$h_1 = L\theta + W\phi$$
$$h_2 = L\theta - W\phi$$
$$h_3 = -L\theta + W\phi$$
$$h_4 = -L\theta - W\phi$$

For the i-th suspension we do the PID control regarding h_i. Since $h_1 = -h_4$ and $h_2 = -h_3$, the number of controlling variables are essentially two.

4.3 Experiment

For the running test we made a model road whose profile is shown in Fig. 12. The peak-to-peak value of the profile height is 120 mm.

We ran the robot over the rough road at a speed of 0.18 m/s and with the suspensions controlled. Fig. 13 shows the result of the experiment. For the comparison, results with no control with fixed suspensions and with free suspensions are shown in Fig. 14 and 15.

From the diagrams we see that the maximum attitude deviation is about ±3° in the control case and much greater in the no control cases. The experiment results clearly shows the effectiveness of the control.

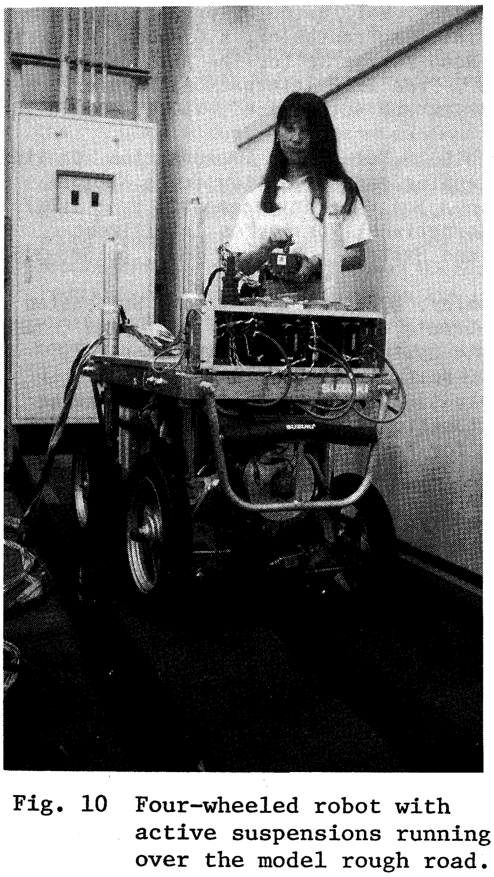

Fig. 10 Four-wheeled robot with active suspensions running over the model rough road.

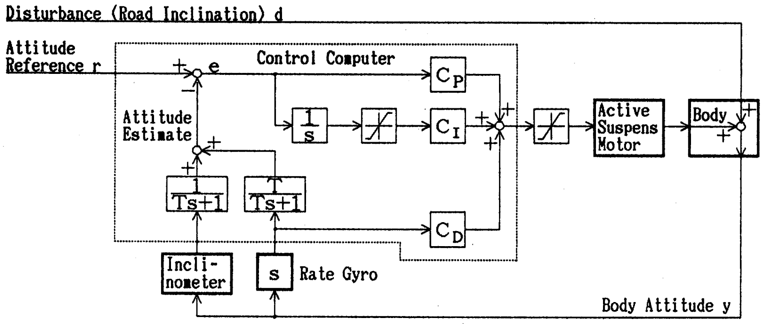

Fig. 11 Block diagram of PID control of the active suspension for the body attitude regulation with the attitude estimation from the inclinometer and the rate gyro signals using a digital filter.

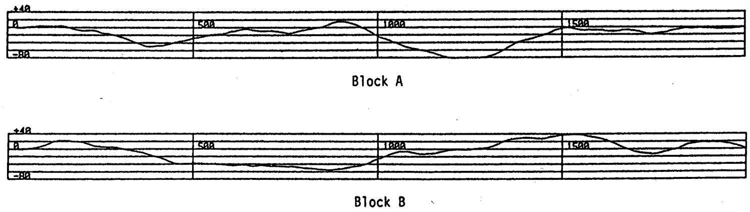

Fig. 12 Profile of the model rough road.

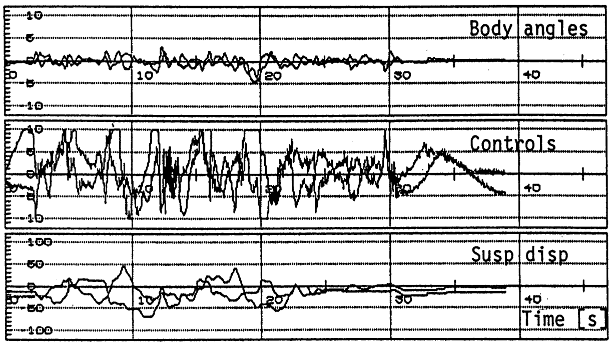

Fig. 13 An experimental result of the body attitude behaviour with PID control of the suspensions during a run over the model rough road.

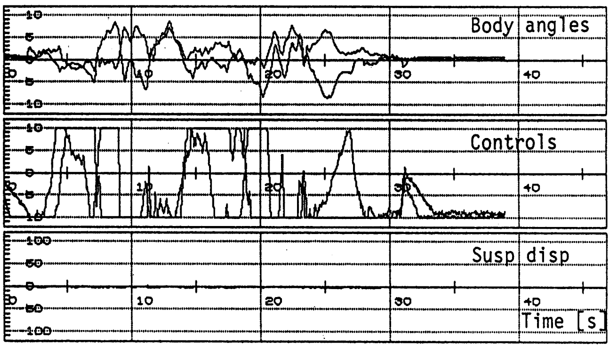

Fig. 14 An experimental result of the body attitude behaviour with no control with fixed suspensions during a run over the model rough road.

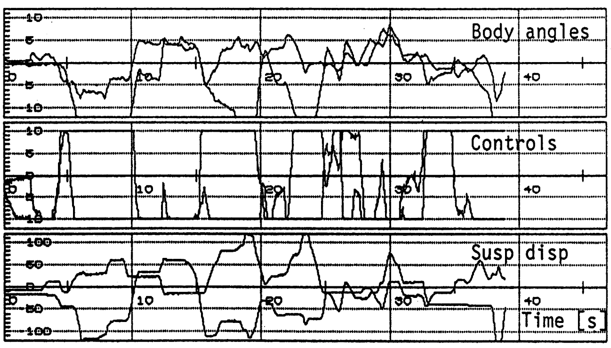

Fig. 15 An experimental result of the body attitude behaviour with no control with free suspensions during a run over the model rough road.

5. CONCLUSION

We have conducted the research of autonomous control of mobile robots to materialize the orienteering functions in a robot. So far we have developed the three described subsystems for the robot. Though it seems very difficult to incorporate the subsystems into a total system for the moment, we will continue our effort towards the realization of such a system.

6. ACKNOWLEDGEMENT

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