CONTROL OF A TRACK VEHICLE FOR CONSTRUCTION AUTOMATION

Mika Matikainen, Hannu Lehtinen
Technical Research Centre of Finland (VTT), SF-02150 Espoo

ABSTRACT

The mobile construction robot system of VTT consists of a track based vehicle, an industrial robot, support legs and process tooling. The main purpose of the control of the vehicle is the navigation and estimation of the position of the vehicle on construction site with an accuracy of ±50 mm. The system takes also care of the support legs and communications between the vehicle and the industrial robot and contains necessary user interface.

The navigation and positioning is based on internal measurements so far. The automatic movements of the vehicle starts from an user defined position in working area. The desired path is sent to the vehicle as movement commands.

The position control with internal sensors stabilizes movements. If amount of manual re-calibration is to be decreased, then external position measurement systems should be integrated to the system. Interfaces and capacity is reserved for them.

1 INTRODUCTION

VTT decided to build a construction robot system which can be moved either using hand controller or autonomously. The vehicle is a Swedish track vehicle, (Lastbärare HLB 9389 Comatech AB, Sweden), which is easy to move in construction areas because garbage does not affect so easily to tracks as it affects to wheels. It also possible to drive this vehicle in stairs. The vehicle can carry a payload of 1000 kg.

2 COMPONENTS OF THE TRACK VEHICLE

The control system of the vehicle has to take care of support legs and two tracks. The power system for legs and tracks is a hydraulic pump which is operated by an AC-motor. The speed of a track is controlled by an analog voltage signal for a hydraulic valve. Valves can be operated manually using hand controller or automatically using analog voltage signal. The signal must be between ± 5 V. The sign of the voltage represents the direction of the movement and the magnitude represents the speed. The speed of the tracks as a function of the valve input voltage is plotted in fig. 1.

Support legs are controlled by binary signals. Legs are lifted and lowered by two hydraulic cylinders which are connected parallel so that the control system needs only one signal to lift the legs and one signal to lower the legs. The support legs get their operation power from hydraulic pump of the vehicle.

Two kind of sensors are mounted to the vehicle to get feedback from system. One absolute rotary encoder is installed in each track to get speed. A gas rate gyroscope is mounted to measure the angular velocity of the vehicle.

The absolute rotary encoder is selected instead of incremental encoder because it easier to read the output of the absolute encoder as the output of the increment encoder. The absolute encoder doesn't need any special card which transfers the output of the sensor to represent the turning angle of driving wheel. All that the system need to read the absolute encoders is standard digital I/O card. The absolute encoder is also protected better against disturbance as incremental sensor. The output of the encoder is pure binary digit, and its resolution is 12 bits. Using the output of the encoder, which represents the turning angle of the driving wheel, and equation (1) can we calculate the speed of the track.

$$v_{tr}=\frac{\Delta a*D*\pi}{4095*\Delta T} \qquad (1)$$

, where Δa is a change from the previous encoder value, 4095 is the maximum output of the encoder, ΔT is the time since the last update and D is the diameter of the driving wheel.

It is important to read the value of the encoder as often as possible, because the maximum turning rate which this kind of sensor can show, is one turn. If we update the encoder measurements often we can detected the cases where the sensor has reached its maximum value and started from the zero point again. Our system read the encoder output once in 50 msec.

Gas rate gyroscope was chosen to the system to measure the turning rate of the vehicle. It is theoretically possible to calculate the turning rate using the speed measurements from the tracks. In the case where the tracks are slipping, it is impossible to get reliable results from these calculations. The solution for this problem is gyroscope. The reason why we selected gas rate gyroscope is that they cheaper than optical gyroscopes and more reliable than mechanical gyroscopes. The output of the gyroscope is analog voltage signal between ± 2.5 volts and the rate range is ± 50 °/sec.

The main problem in using gyroscope is the drift in the output. Even if the gyro does not move the output changes slowly. The reason is the turning of the Earth around north south axis. Drift is usually eliminated for example by using feedback from a compass. But the compass is not very reliable equipment in construction area, because of occasional electromagnetic disturbances, which are difficult to eliminate.

The drift in a gas rate gyroscope changes continuously, sometimes even the drift is nonlinear. We have estimated that the drift is about 1.98 °/s/h in a case. The drift is calculated before movements by averaging ten previous output values of the gyro. When we start to turn the vehicle we subtract the calculated value from the gyro measurements in order to eliminate the drift. The method does not eliminate drift which occurs during the movement, but the normal 90° turn movement lasts only about 30 seconds. The orientation error during that time caused by the drift is about 0.5°.

The I/O signals for the valves of tracks and from the gyro are analog (± 5 V) and from the encoder digital. The encoder output values are open collector binary digits transferred to TTL-level on a VTT made board. Effect for the valves of support legs comes from

24 V power source of the vehicle. For the analog and encoder signals was chosen RTI-820 board and STB-HL02 analog panel from Analog Devices. The 24 V signal level is controlled by an RTI-817 board, which can also generate interrupt to the bus. All boards are PC-compatible products. The only disadvantage in these boards is that the program needs three commands to write an analog voltage signal which take relatively long time. The chosen combination is flexible system for development; the system could be transferred later on for a more dedicated board.

The core of the control system is the operating system. For autonomous vehicles it is important that the feedback from the system and the surroundings can be read as often as possible. That is the reason why we selected Canadian real-time multi user operating system QNX [1]. The operating system offers both development toolkit for the programmer and surroundings where to run programs [1]. In a multi user system it possible to run several programs at the same time and also to control them from another terminal via network simultaneously. In QNX system it is possible to get internal clock ticks in several intervals, minimum interval is 1 ms. We selected to use 50 ms time interval in our programs which means that we use 5 ms clock ticks to get accurate response. The reason for this is that the accuracy of the clock is one tick, if we use 50 ms clock ticks the accuracy of the clock pulses is 50 ± 50 ms but if we use 5 ms clock ticks the accuracy is 50 ± 5 ms.

3 ONLY TWO KIND OF MOVEMENTS

3.1 Path Planning

The path in working area for the vehicle consists of both linear and curved movements. The vehicle is supposed to move aligned with the wall so that its motions are mainly linear. This is done to reduce the positioning error caused by slipping tracks in turnings. It is recommended to compose the path so that there is turnings only when the vehicle moves from one wall to another wall. So far the path planning is done by the operator, but in the future it would be reasonable to make a program which calculates the optimum path for vehicle using for example artificial potential fields [2].

3.2 Calculating speed orders and controlling the speed of a track

In situations where there is no slipping in the tracks we can calculate the trajectory speed of the vehicle using equation (2).

$$V_v=\frac{V_{ltr}+V_{rtr}}{2} \tag{2}$$

, where v_{ltr} and v_{rtr} are the measured speed of the left and right track. The angular speed of the vehicle can be either measured from the gyroscope or in some cases estimated according to equation (3).

$$\omega_{est}=\frac{V_{rtr}-V_{ltr}}{r} \tag{3}$$

, where r is the distance between the tracks.

From equations (2) and (3) we can solve the equation (4) which is used to calculate the speed order for each track when we know the speed orders for angular and trajectory are known.

$$\begin{bmatrix} V^o_{ltr} \\ V^o_{rtr} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{r}{2} \\ 1 & \frac{r}{2} \end{bmatrix} * \begin{bmatrix} V^o_v \\ \omega^o \end{bmatrix} \tag{4}$$

v^o_v is the trajectory speed order for vehicle and ω^o is the angular speed order for vehicle. If we have a constant turning radius and we want to calculate the speed orders for track using only the speed order for angular speed we get an equation (5).

$$\begin{bmatrix} V^o_{ltr} \\ V^o_{rtr} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{r}{2} \\ 1 & \frac{r}{2} \end{bmatrix} * \begin{bmatrix} R*\omega^o \\ \omega^o \end{bmatrix} \tag{5}$$

Now that we are able to calculate the speed orders for the left and right tracks we have to take care of maintaining the desired speeds. For that purpose the control system of the vehicle has a differential PI-regulator.

$$v^o(t) = v^o(t-1) + K_{PS}*(e(t) - e(t-1)) + K_{IS}*e(t) \tag{6}$$

, where

$$e(t) = v^o(t-1) - v_{tr}(t) \tag{7}$$

is the control error, v_{tr} is measured value of a track, v^o is the speed order of a track and K_{PS} and K_{IS} the multipliers of gain and integral terms.

3.3 Linear Movements

The speed of the tracks during linear movements is constant 0.07 m/s most of moving time. The vehicle is accelerated to this speed during 1.5 s. It is reasonable to use such a long acceleration time to stabilize the movements because sudden movements may move pay-load. Also some positioning error might happen because of sudden movements. Near the goal point the control system starts to decelerate the speed to certain value. The vehicle will move with this speed until it has reached its goal point where it stops.

The control of linear movement is done by feedback from angular velocity and orientation estimates of the vehicle. The angular velocity estimate is calculated using the equation (3). It is impossible to use the gyroscope to measure angular velocity during linear movement because the noise in the measurements is much more higher than the real angular velocity.

During the linear movement the control system tries to keep the angular velocity zero and maintain the orientation. This is done by using modified P-regulator introduced in equation (8).

$$\omega_{order}(t)=\omega_{set}+K_{PL}^{\omega}*(\omega_{set}-\omega_{est}(t))+K_{PL}^{\Omega}*(\Omega_{start}-\Omega_{est}(t)) \quad (8)$$

ω_{set} is the desired angular speed, $\omega_{est}(t)$ is the estimated angular speed, Ω_{start} is the orientation of the vehicle at the beginning of the movement, $\Omega_{est}(t)$ is the current orientation, K_{PL}^{ω} is the gain of the angular speed feedback and K_{PL}^{Ω} is the gain of the orientation feedback. Using the equation (8) the control system calculates an angular speed order. Then control system calculates the speed order of each track using the equation (4). The speed orders for each track are then transferred to the speed controller (6) which maintains the calculated speed order. The system calculates then the output voltage corresponding to output speed of equation (6). This voltage is the control voltage of a hydraulic valve. The output voltage can be calculated from the characteristic curve of a track, plotted in figure 1. In figure 2 is presented the block schema how to control linear movements.

The position estimator during linear movement is presented in equations (9) and (10).

$$X(t)=X(t-1)+\Delta T*\frac{V_{rtr}+V_{otr}}{2}*\cos\Omega(t) \quad (9)$$

$$Y(t)=Y(t-1)+\Delta T*\frac{V_{rtr}+V_{otr}}{2}*\sin\Omega(t) \quad (10)$$

The orientation of the vehicle is calculated from the speed of the tracks using equation (11).

$$\Omega(t)=\Omega(t-1)+\Delta T*\frac{V_{rtr}-V_{ltr}}{r} \quad (11)$$

3.4 Curved Movements

Curved movements are carried out with constant angular speed and turning radius. Angular speed is 0.045 rad/s and radius 1.5 meters. The controller of curved movement estimates the orientation of the vehicle during movement and stops the vehicle when it has reached the desired orientation. Also in curved movement there is an acceleration at the beginning of the movement and a closing speed when the vehicle is near its final orientation. The speed orders for the track are evaluated from the desired angular speed using equation (5). This is done because the equation (3) does not give reliable trajectory speed during turnings because of the track slipping.

The feedback from the system during curved motions is done by measuring the angular speed using gyroscope. To keep the vehicles angular speed in specified value we use differential PI-controller.

$$\omega^{o}(t)=\omega^{o}(t-1)+K_{PC}*(e(t)-e(t-1))+K_{IC}*T*e(t) \qquad (12)$$

,where

$$e(t)=\omega_{nim}(t)-\omega_{est}(t) \qquad (13)$$

is the control error, K_{PC} and K_{IC} are the multipliers of gain and integral terms.

The method of controlling the track speed in curved motions is the same as in the case of linear motions. First we calculate the angular speed order and from it we calculate the corresponding track speeds which we transfers to the track speed controller.

The position and orientation estimation differs from the case of linear movement. Because we do not get reliable trajectory speed from equation (2) we have to replace it with equation (14).

$$V_{V}=\omega*R \qquad (14)$$

, where R is the turn radius. Because of the acceleration, deceleration and the slipping the vehicle does not make exactly round movements, as we hoped. Thus we have to experimentally define different constants for x-dimension and y-dimension. If we try to turn the vehicle left 90° and the starting point is (0m ,0m ,0°) we go to point (1.8m , 1.5m, 90°). From these points we can calculate the constants R_X 1.8 and R_Y 1.5. We can use these values also when we turn less than 90°. The position and orientation estimator which is used during curved movements is introduced in equations (15)-(17).

$$X(t)=X(t-1)+\Delta T*\omega_{est}(t)*R_{X}*\cos\Omega(t) \qquad (15)$$

$$Y(t)=Y(t-1)+\Delta T*\omega_{est}(t)*R_{Y}*\sin\Omega(t) \qquad (16)$$

$$\Omega(t)=\Omega(t-1)+\Delta T*\omega_{est}(t) \qquad (17)$$

3.5 Results

The accuracy of the positioning system is ± 10 mm in linear motion and ± 30 mm and ± 4° in curved motion. These results are from the tests where we drove the vehicle a little forward before we started the movements. This way we eliminated the effect of slack in the tracks. When we did not eliminate the gap the position errors were three times larger than in the first case. It is obvious that during the work process vehicle have to change its direction several times, thus we can not leave the gas in the track without any notice. This means that the total accuracy of the vehicle is ± 90 mm and ± 4°. In figure 3 is plotted movement where the vehicle drives first straight ahead and then turns 90° to the left. The line represents the estimated path and the star the real position of the vehicle after movement.

4 SOFTWARE RUNNING IN THE PC

The software of the control system contains five different tasks which have different priorities. And which are run in different intervals.

One task is purely for navigation and piloting the vehicle. Navigator task updates the position of the vehicle and calculates and writes the speed orders for the tracks. After that it stops until it receives a new clock signal.

The clock task sends once in every 50 ms a signal to the navigation tasks. This way we can guarantee that the navigation task will work in certain constant periods.

The emergency task checks once in a every 50 ms if the emergency circuit has opened. This mean that the vehicle has bumped against some unknown obstacle. If this happens this task will command navigator task to put the speed orders for the tracks to zero. Emergency activites should be programmed as an interrupt handler instead of polling of I/O, but we have not succeeded in this so far.

By using the operator interface task the operator can check some information about the vehicle like the position and speed etc. Operator can also feed moving command. This task is the so called father task for every other task in the system. When we start to run the control system this task creates all the other tasks before its will start to work as human interface. At the beginning of the operation this task asks the path of the vehicle from the robot. This task works also as a link between the robot and the control system. It will inform the robot to start to work when the vehicle has reached a processing position.

The fifth task is a message link between Monitor task and the Navigator task. All the messages which Monitor task sends to Navigator task will be send directly to the Navigator task. But when the Navigator task sends something to Monitor task the message will come first to this task which sends them further to the Monitor task. This way we can prevent the situation where both the Monitor task and the Navigator task are trying to send a message to each other at the same time. This situation could block the whole control system. The situation might happen in a case where the operator wants to check for example the position. In this case the Monitor task would send a message to the Navigator task to send the position. If the vehicle has reached its goal point at the same time, the Navigator task would send a message to the Monitor task that the vehicle has completed the movement order. In figure 4 it is plotted the structure of the control system.

5 FUTURE DEVELOPMENT

There is two main things in this control system which we have to concentrate in future. First case is the installation of the external positioning system. As we can see we can not operate long time at the desired accuracy of ± 50 mm. In some cases it is possible to use the robot to check the accurate position of the vehicle from known landmarks like walls and doors but it is not always possible. With the help of external positioning system, it would be easy to eliminate some of the positioning error, and the accuracy of the vehicle could be much better. Anyway this kind of internal positioning system developed is a good basis when we want to install a external positioning system which are in some cases too slow for real-time positioning.

The automatic path planning program is another unit to be developed. The control system needs it also when we have noticed that the vehicle has lost its accurate position. After we have calibrated the exact position the system should change its moving commands, which it has not done yet, automatically so that the vehicle really goes to the right positions also in the future.

6 REFERENCES

[1] QNX Manual. Quantum Software Systems Ltd. Kanata South Business Park. 175 Terrence Matthews Crescent. Kanata, Ontario K2M 1W8. Canada

[2] C. W. Warren. Global Path Planning Using Artificial Potential Fields. In Proceedings of the 1989 IEEE International Conference on Robotics and Automation, pages 316-321.

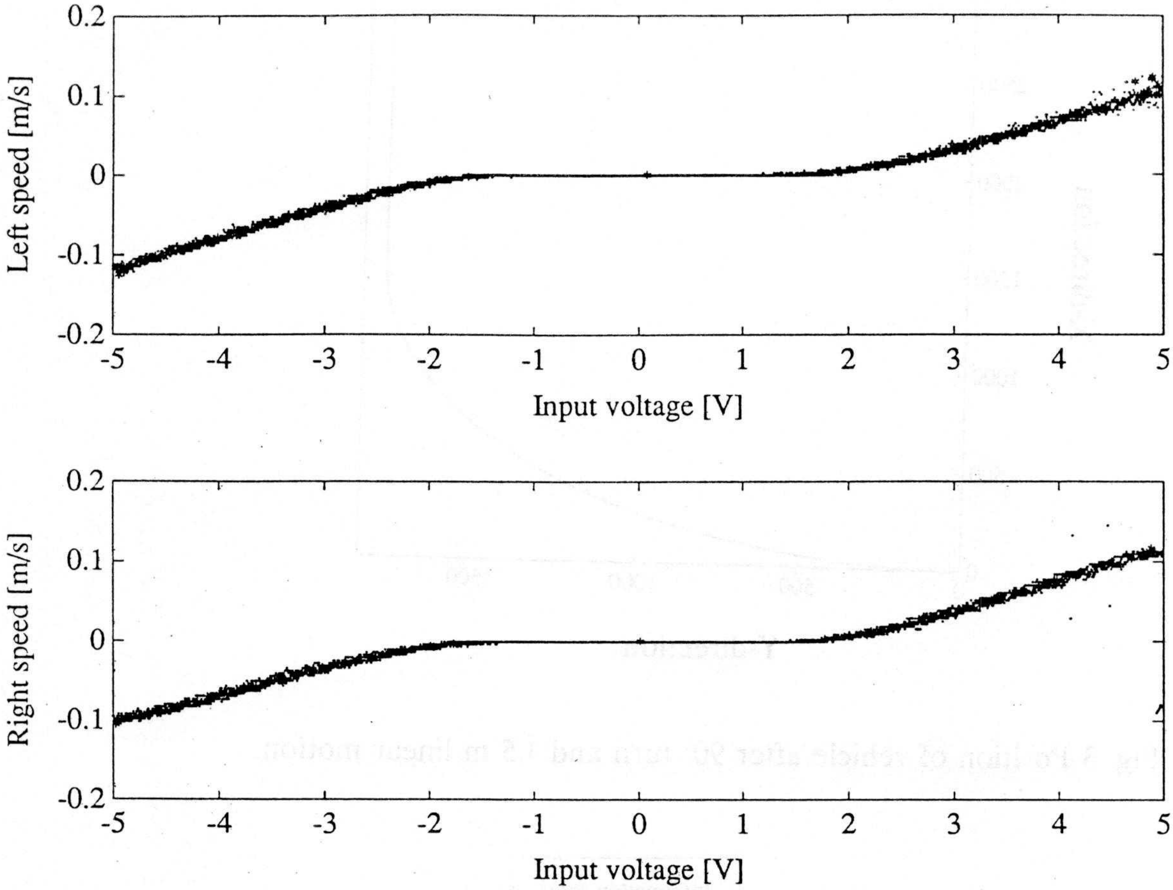

Fig. 1 Speed of tracks as function of voltages.

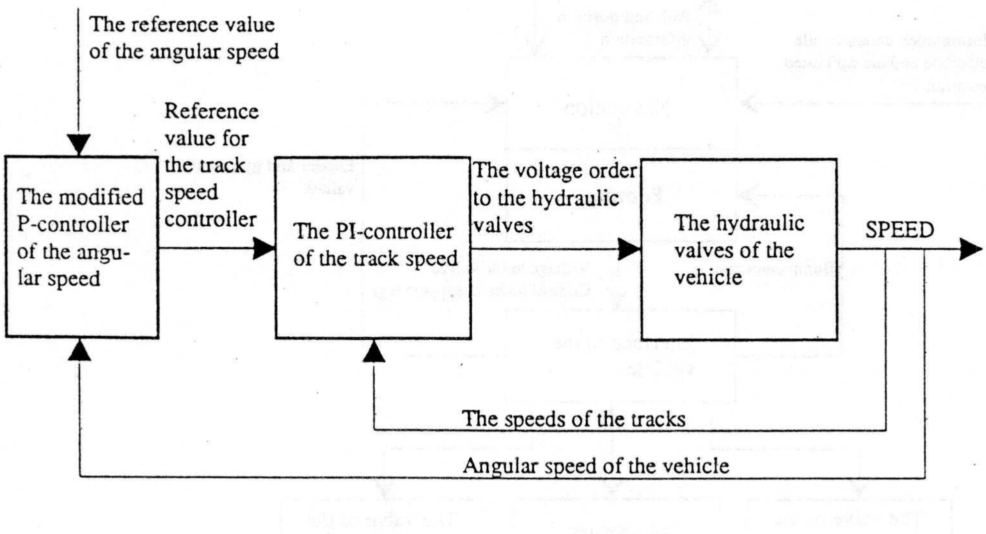

Fig. 2 Control of linear motion

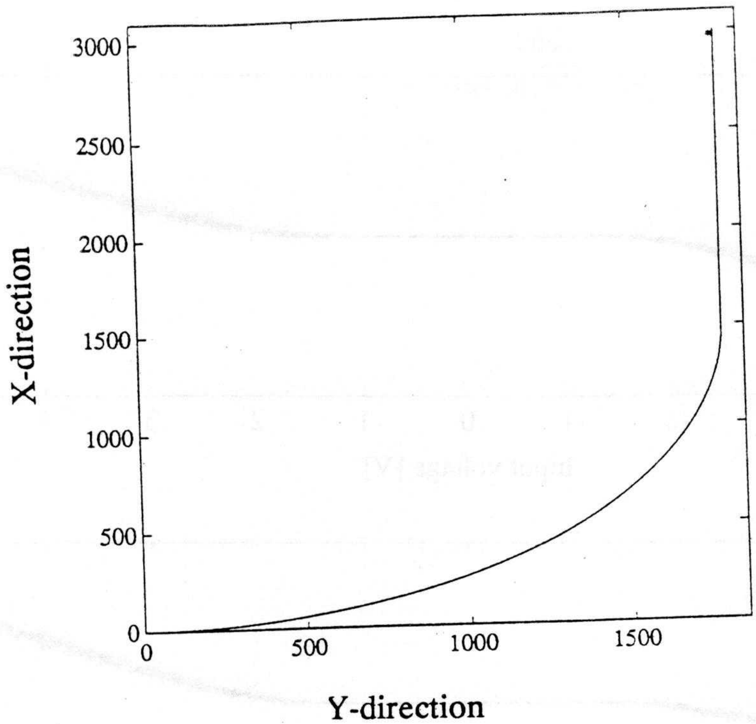

Fig. 3 Position of vehicle after 90° turn and 1.5 m linear motion.

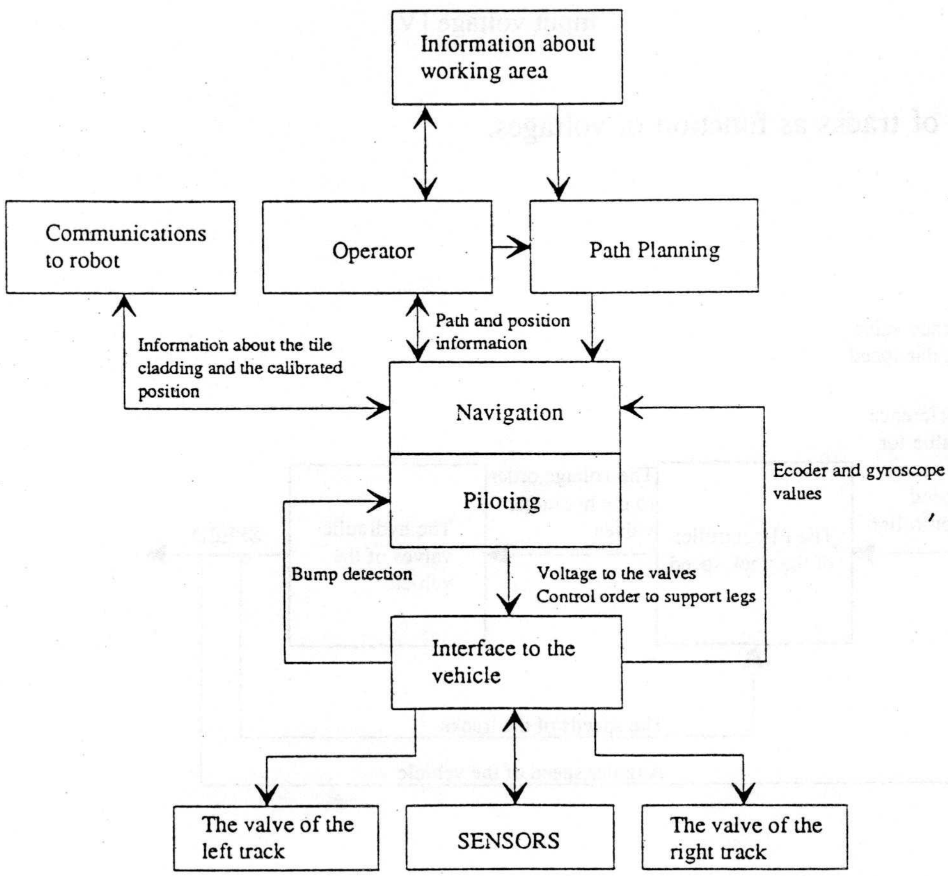

Fig. 4 Structure of control system.