Technical Paper
on

Reflex System for Collision Avoidance of a Robot

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Contents

Introduction

When a robot is designed, we try to model it along the lines of the human body and brain. This is because the human body and mind is the best machine around. But there are certain shortcomings that we'd like to improve upon. For e.g. the human brain tends to get distracted after doing the same kind of work for a long time.

One of the amazing things about the human body is the inbuilt reflex system. The idea of the reflex system is to take the load off the brain and to provide spontaneous reaction. In normal circumstances, the nervous system sends electric pulses to the brain via the spinal cord. The brain then analyses the pulses and hence decides what to do. However if somebody is pricked by a pin, the electric pulses go to the spinal cord where a reaction is produced. This reaction does not depend so much on what has pricked you, but more on where you have been pricked and actuation takes place accordingly. This is because there should be only one reaction, which is to move away from the pin.

If we look at the central processor of a robot as the brain, and the mechanical systems as the body, then there should be a system analogous to the reflex system also. The system that we have designed aims to do just that. We've further improved this system by extending the sensing to outside the body, and hence used it for collision avoidance.

Problem at Hand

Every robot has a central processor that is constantly calculating and analyzing data. To show this, let us take an example of a robot equipped with machine vision.

Suppose the robot uses a camera that gives 128 x 128 resolution image of 4-bit color format that is a minimum for good image acquisition. This would mean exactly 256K per image. For a fast reaction, this image acquisition should take place at least 16 times per second, which then means the processor has to deal with 4 MB per second !!! On top of this image processing activities (like fourier analysis, etc.) are very processor intensive.

Along with machine vision, the robot also has other mechanical and/or sensory devices to constantly monitor and control. For e.g. if a robotic arm has 6 axes, then for each forward kinematic calculation, it has to multiply 6 (4X4) floating-point matrices, which shall increase with precision. Similarly for inverse kinematic calculations, more processor time will be needed.

Other calculations which also require large processor time are the path/trajectory planning, A.I., communications, dynamically monitoring all actuators, etc.

Thus we see leaving the exact calculations of finer maneuvering to another processor free system would be wise.

The Present Scenario

The most obvious application of this system is the automobile. Some work has already been done in this field, and lots of proposals have been made. Some of them are being listed:

- One of the solutions is the use of the Global Positioning System to avoid collisions. The absolute coordinates of the vehicle are obtained by the GPS system along with those of the other vehicles surrounding it. Based on this data, vehicle is navigated. There are some very obvious problems with this system.
  - The accuracy of the GPS system has to be very high (of the order of cms.) for the system to be safe.
  - This system fails miserably for objects of which the coordinates aren't available, like pedestrians, conventional cars, cows, etc. This makes it very difficult to be implemented practically.
  - The position of the GPS on the car will have to be standardized for all the cars.

- Another proposal is to use inter-vehicular communication for navigation. In this system, the cars constantly communicate with each other and inform the others about their *relative* positions. The flaws with this system are:
  - There is too much of communication taking place around a particular vehicle, which slows down the decision-making process.
  - This system also has the same problem as that of the GPS system, which is it fails for objects not equipped with the same communication system.

- An extension of the system used in non-mobile manipulators where the environment is fixed for mobile robot is the use of Machine Vision and other sensory devices to map the environment. The environment is then continuously analyzed using cameras (more than one) and a path is decided for the vehicle to move on. The problems with this system are:
  - The processor will have to be very fast to be able to process and integrate the data from different sensors, and then decide the trajectory.
  - The cameras and sensors used for the purpose of environment mapping are very costly.

- To remove the above-mentioned shortcomings, one way is to use the physical contact and proximity sensing system. In this system cheaper sensors are used to obtain only the necessary data and react after the vehicle reaches a minimum distance from the nearest object. Thus till the vehicle is very close, this system is disabled. This system does not predict collisions and take corrective action, which is a matter of concern at high speeds.

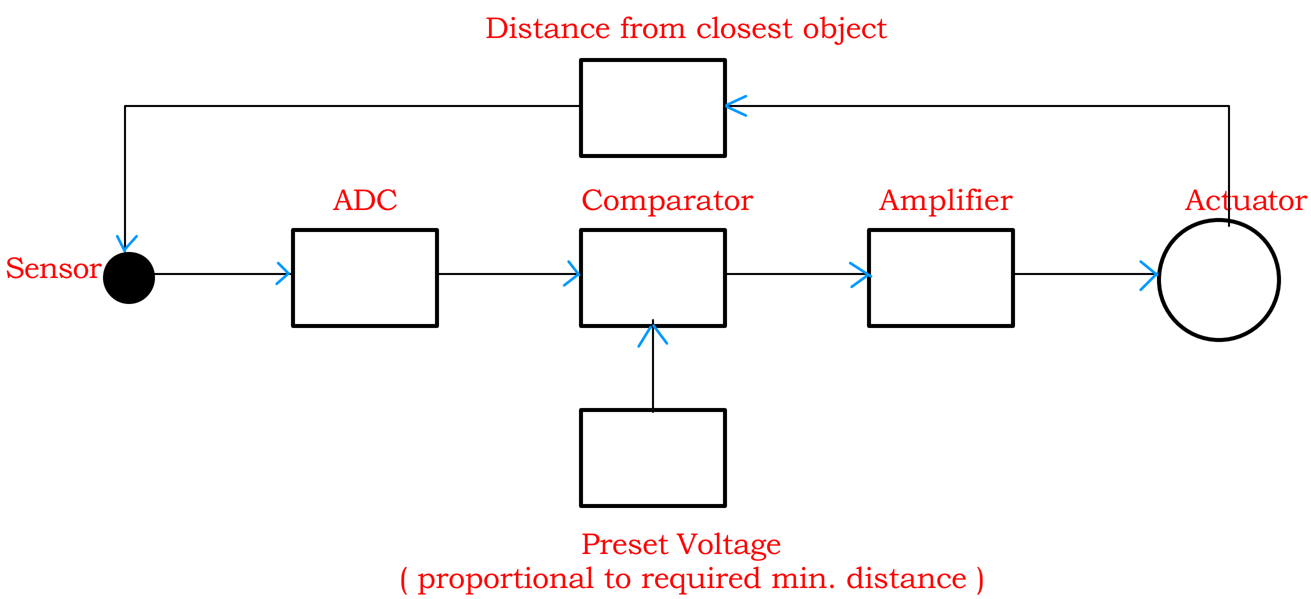
Proposed System

Keeping these shortcomings in mind, we've designed a system that can foresee collisions and take necessary action so that collisions are avoided without using a lot of processor time. This system can be implemented on top of any existing mobile robot to safely navigate it through difficult environments, without the need of complex synchronization of this system with the other systems of the robot. The proposed Reflex system is basically composed of two components running in parallel with each other.

The V System

This system is designed so that the robot keeps a minimum distance from the nearest objects on all sides. We use a sensor that gives a voltage output proportional to the distance of the nearest object. This voltage is compared to the preset voltage that corresponds to the minimum distance, and the output is fed to the actuator. This preset voltage can be changed as per requirement even during runtime.

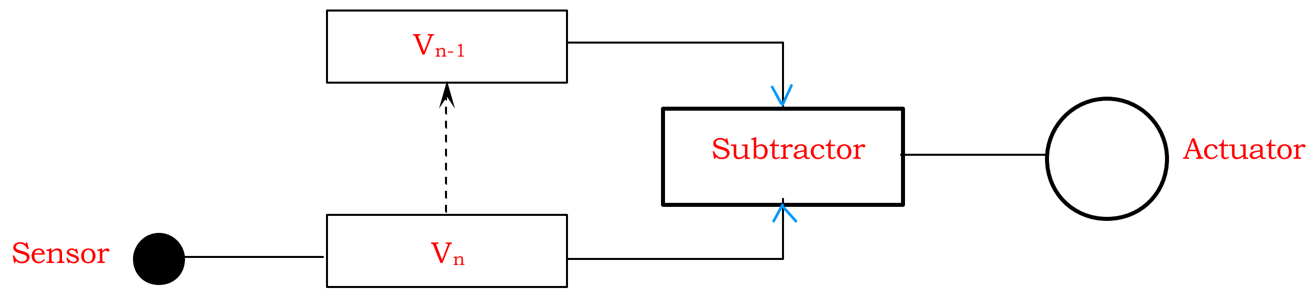
V SYSTEM BLOCK DIAGRAM



The dV System

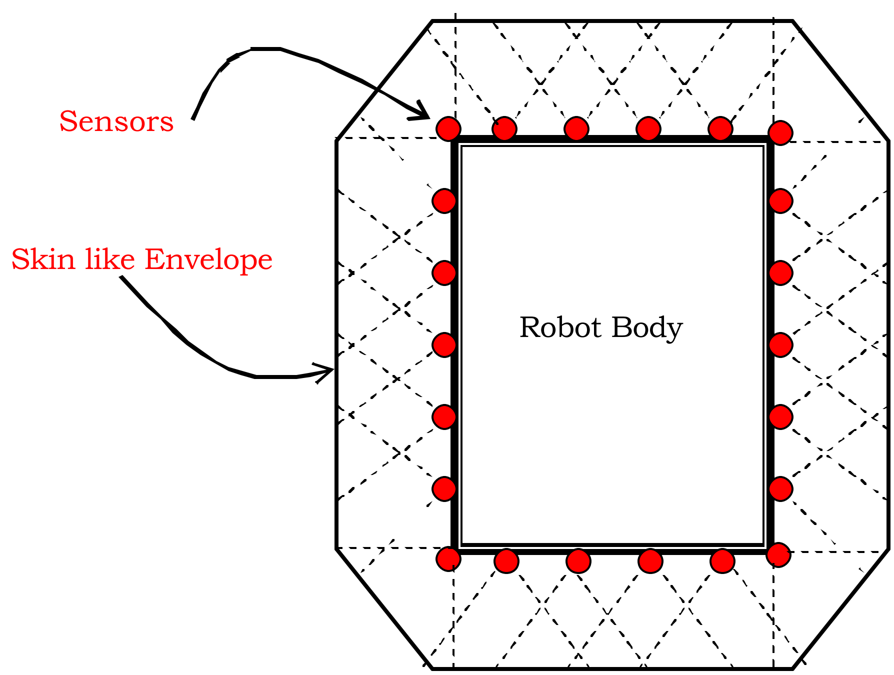
This system ensures that no collision takes place. Instead of using the preset value of the voltage, this system uses the difference of two consecutive voltage outputs to foresee collisions and take necessary action. Suppose the present voltage output is V_n, and the previous value of voltage is V_{n-1}, then the difference $(V_n - V_{n-1})$ is taken as dV. Positive sign of dV corresponds to reducing distance and negative sign to increasing distance. Also, the magnitude of dV corresponds to the relative speed of approach of the nearest object. The necessary action is decided by giving this dV to the actuator. The actuator decides the direction of movement based on the sign of dV, and the magnitude of actuation can be varied linearly or exponentially with the magnitude of dV.

<u>dV SYSTEM BLOCK DIAGRAM</u>



These two components working together are analogous to the extended reflex system of the body. The envelope produced by the sensors put together forms a 'skin' around the robot. If this 'skin' is 'pricked', the system gets enabled and pushes the robot away from the 'pin'. The system also makes sure the robot goes away faster if the 'pin' is moving faster. Thus there is no physical contact between the 'pin' and the robot, unlike in the human body.

<u>IMPLEMENTATION OF THE 'SKIN' LIKE ENVELOPE</u>

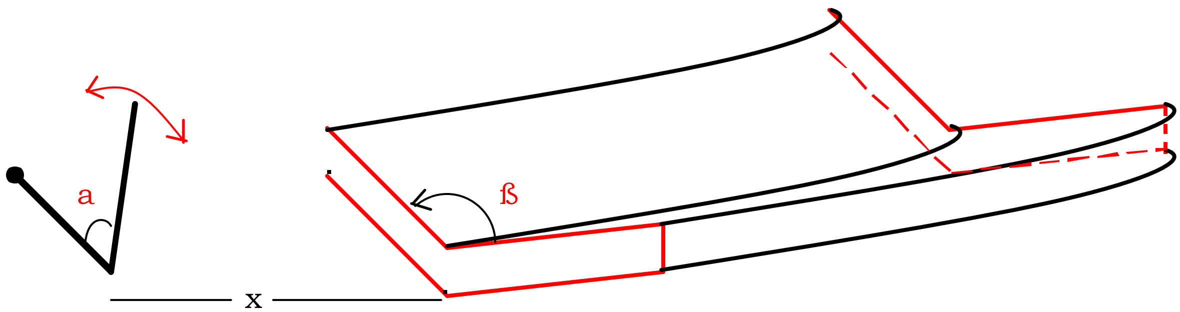


This system is designed in such a way that actuation takes place without requiring ANY processor time, and can be easily built into an existing robot design.

Applications

Mobile Manipulators

The system can be applied in solving the orientation problem for mobile manipulators. The work done till now has been concentrated on finding the EXACT coordinates and orientation of the manipulator of the robot at a particular point in time so as to avoid collision. But this job can now be reduced to just finding the approximate orientation of the manipulator. The rest of the job can be performed at the `reflexive level' just as in the case of humans. As shown below, if the manipulator has to be moved through a long tube of the shown shape, then the problem is reduced to just seeing the shape in advance and finding the approximate orientation of the manipulator (i.e. the angle ß), which is a comparatively easier task if the robot has complete knowledge of the own size.



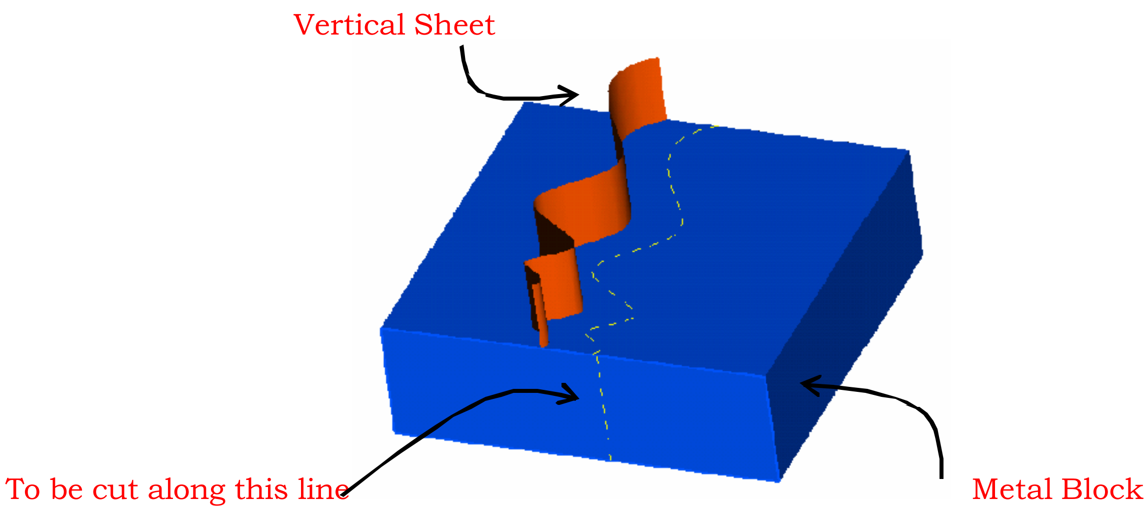
For the moving manipulator if we know the speed of the manipulator, the time in which it will cover the distance x is t = x / speed.

Thus we know that we must change the angle of the manipulator from a to ß in time t. Once the manipulator reaches the tube at an angle close to ß the reflex system takes control and causes the orientation of the manipulator to get fine tuned so that there is equal clearance on all sides inside the tube. Thus we don't need the exact coordinates of the manipulator for just moving without collision.

Water-Jet cutting and Welding machines

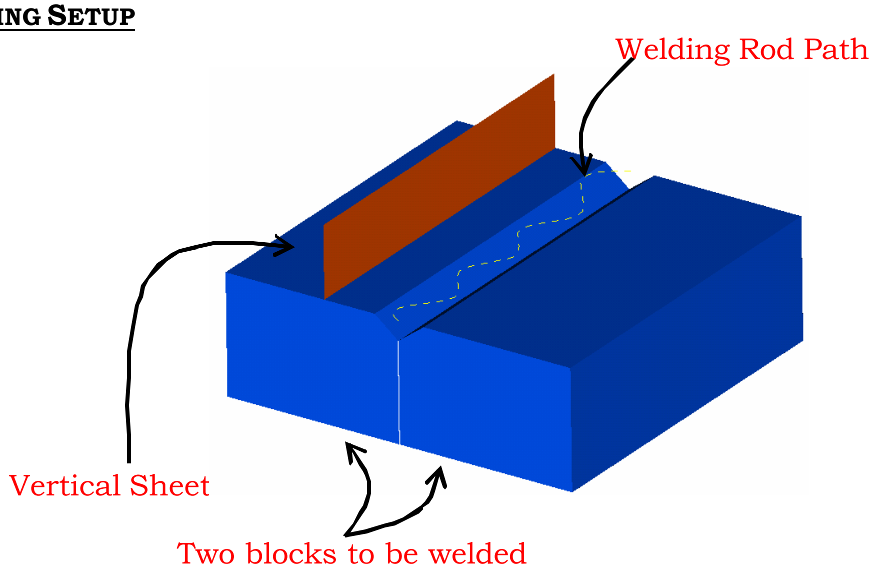
The accuracy of water cutting and welding machines can be increased manyfolds by the use of the above system as a copying system. Say that a metal block has to be cut in a certain shape, then we can use a vertical sheet in the shape of the cut and a robot with only the V system implemented can be used to guide the water nozzle as it will constantly maintain a specific distance from the vertical sheet.

WATER-JET CUTTING SETUP



The amplitude of oscillations about the mean position can be controlled by just controlling the clock pulse given to the stepper motor used to guide the nozzle. For the waterjet cutting machine the clock pulse can be made as high as possible so that we get a smooth cut (as the oscillations will be neglegible) while in the case of a welding machine the oscillations can be made larger so as to prodive proper welding range coverage, as shown below in the figure.

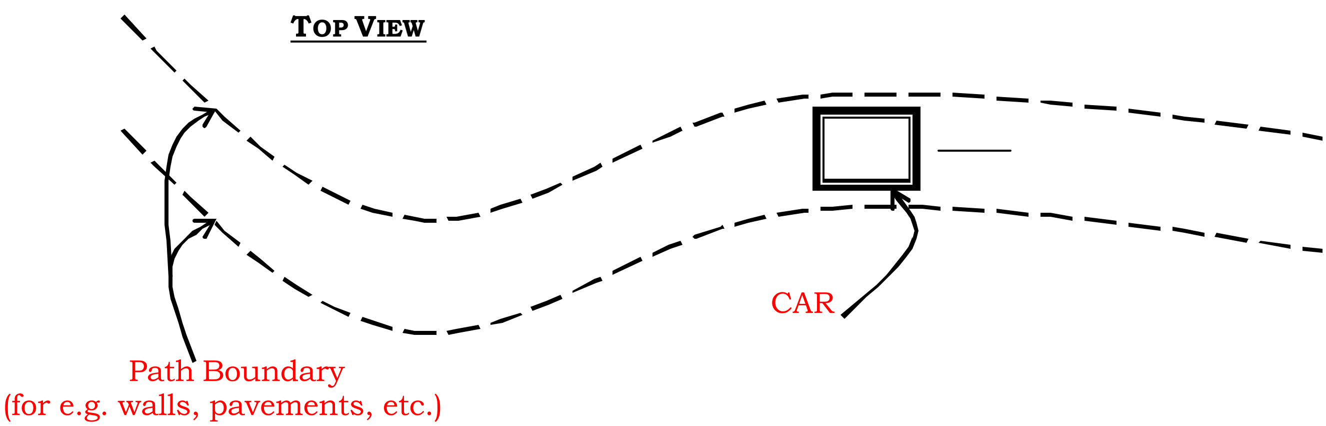
WELDING SETUP



Self Maneuvering Vehicle

Need has always been felt to make vehicles' steering system automatic. These vehicles can be not just cars, buses, etc. but also special purpose vehicles where a human driver is not safe, like underwater exploration, army purposes, mining, radioactive environments, extreme temperature zones, outer space research, etc.

The reflex system, used in conjunction with machine vision is a complete car navigation system. The machine vision "sees" the road and the objects on it, and decides approximate path of the car. For e.g. if a car is directly in front, then processor decides (with the machine vision data) if it should overtake, turn left or right at a crossing, or if it should stop (at traffic lights, for e.g.). The reflex system takes care of the finer maneuvering and collision avoidance.



The car has an array of sensors along both its side, which keep detecting the distance of the nearest object. Out of the values returned by each sensor, the largest value of output (i.e. the minimum distance) is taken and used in the V system as follows.

Let these maximum values be called V_L' and V_R', from the left and the right sensor array respectively.

Let the preset voltage (corresponding to minimum distance) be V_O.

Then the error voltage be $V_{L/R} = V_{L/R}' - V_O$

This error voltage is used by the actuator to control the steering system as given below

Only Right Sensors Enabled Value into actuator = V_R	0	Do nothing
	+ ive	Steer Left
	- ive	Do nothing
Only Left Sensors Enabled Value into actuator = V_L	0	Do nothing
	+ ive	Steer Right
	- ive	Do nothing
Both Sensors Enabled Value into actuator = $V_L - V_R$	0	Do nothing
	+ ive	Steer right
	- ive	Steer left

Table - 1

Thus if there is an object on the right (or left) it maintains a minimum preset distance from it. If there are objects on both sides, then the car will be maneuvered to the middle. This is the implementation of the V system.

The V system is not capable of detecting collisions, and operates at a constant speed, irrespective of the velocity of approach of an obstruction. Thus the dV system is used to foresee collisions according to the velocity of approach, and steer accordingly to avoid it.

The dV system uses two values of voltages that are dV_L and dV_R.

$dV_L = V_{Ln}' - V_{Ln-1}'$
$dV_R = V_{Rn}' - V_{Rn-1}'$

The steering is done as follows :

$dV_L - dV_R$	0	Do nothing
	+ ive	Steer right
	- ive	Steer left

Table - 2

The degree of turn depends upon the magnitude of dV.

Thus we've designed a self- maneuvering car, using the reflex system for collision detection. The circuit implementation of this has been discussed later in detail.

Other Applications

There are numerous other applications of this system due to its flexibility, like –

- Automatic vacuum cleaners – Machine Vision (or some other sensor) can be used to detect dirt, and decide the direction of movement, while the reflex system can be used to maneuver it away from obstructions.

- Self-Maneuvering Wheelchair – can be built upon the same lines as the self-maneuvering car. This wheelchair shall benefit handicaps a lot.

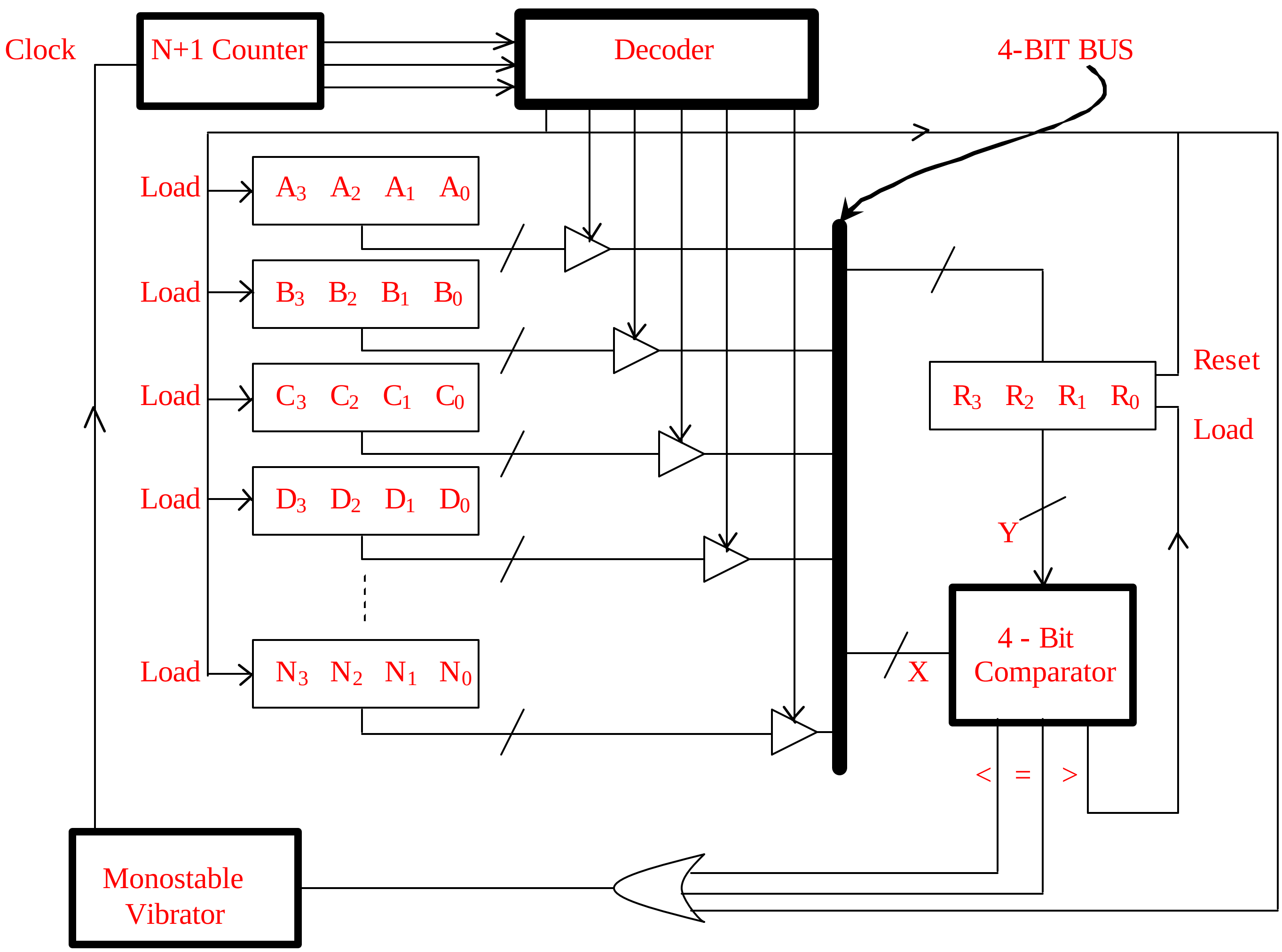
- Space ships – Though already auto piloted, these ships can have a reflex system to guide them through asteroid belts, etc. which has been impossible till now.

- Future Vehicles – With the increasing number of cars on the roads today, it is inevitable that there will be flying cars in the future. The reflex system can be adapted to be used in three-dimensional navigation.

Circuit Implementation of Self Maneuvering Vehicle

The circuit can be divided into four stages. **The Input Stage** consists of the acquisition of voltages (digital) from the sensor array (right and left), selecting the highest value of voltage from each side and storing it in a register. This stage will be explained only in terms of one side, i.e. left or right.

THE INPUT STAGE



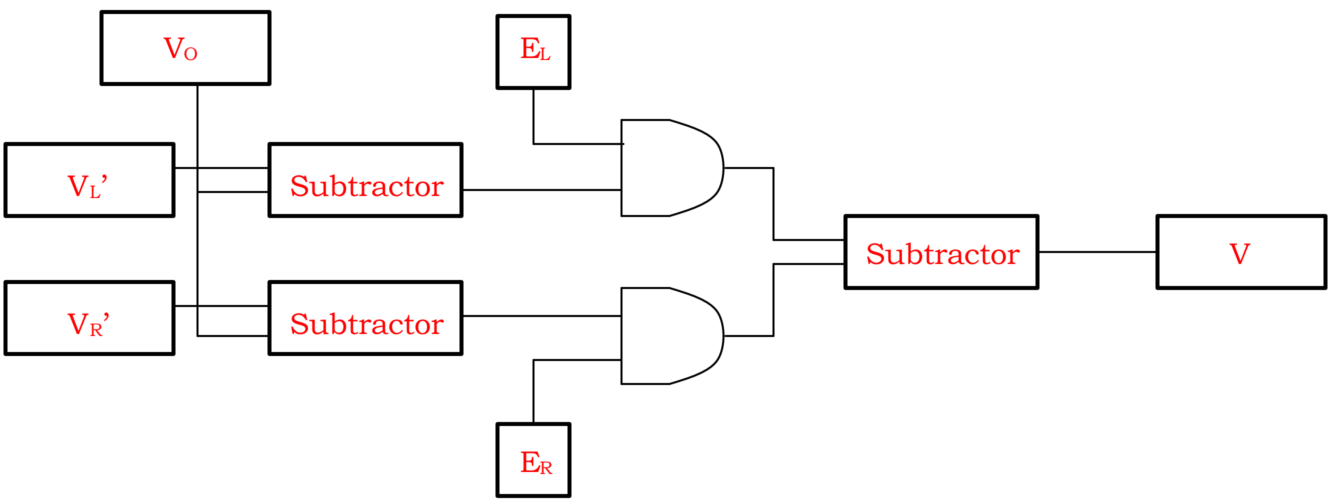
This is an asynchronous circuit that subsequently compares the values from various registers to that stored in a register R and updates the value of R if the other is bigger. The first output of the decoder loads new values into the N registers and clears the register R. After each comparison the counter is incremented with the help of a monostable vibrator. The output of the counter goes to the decoder which in effect changes the value on the bus to the next stored register value by activating the correct tristate buffer. Another implementation of the same can be with the use of a multiplexer bus. At the point of clearing, the value of R is copied into another register $V_{L/R}$'.

This value of $V_{L/R}$' is used in **the V system**. In this stage, there are two flip-flops, namely E_L and E_R, which are set to true if the sensor array of the respective side is enabled. There are two more registers which store the value of $V_{L/R}$, by subtracting the preset voltage V_O from $V_{L/R}$'. The necessary action is taken as per the criteria described in Table – 1, for which we define the following equations :

$V_L = V_L' - V_O$
$V_R = V_R' - V_O$
$V = E_L V_L - E_R V_R \quad = \quad V_L' - V_R'$; (Center of objects on both sides)
$\quad = \quad -(V_R' - V_O)$; (Minimum distance from right side)
$\quad = \quad V_L - V_O$; (Minimum distance from left side)

This value of V derived from the equation has a sign and magnitude, which are together used to determine which side the car needs to be steered. This value of V is obtained as shown in circuit below.

THE V SYSTEM

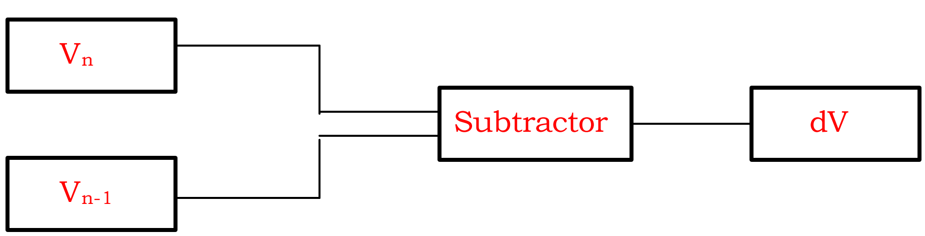


The next system is the **dV system** where the following equations are used to obtained the value of dV which is effectively the derivative control of the steering system.

$dV_L = V_{Ln}' - V_{Ln-1}'$
$dV_R = V_{Rn}' - V_{Rn-1}'$
$dV = dV_L - dV_R$

This value of dV obtained above also has a magnitude and a sign bit and is implemented in circuit form as shown.

THE dV SYSTEM



The value of dV obtained above is used for two basic purposes in the steering system

- To make the steering proportional to the rate at which an object is coming closer to the car.
- To move the rotor of the stepper motor in the reverse direction even when steering in a certain direction i.e. in reducing the amount of angular displacement of the motor.

This is implemented in the **Output Stage** as shown below. The Output Stage is the most important stage of the system and is also the most complicated. The stepper motor, which is used for steering the vehicle, can be made to rotate in one direction step by step if we make the inputs (say a,b and c) high one at a time in one sequence and the other direction if the sequence is reversed. Let us assume that the mechanical systems are such that if we give the sequence abca… the car turns right and left if the sequence is acba…Also let us assume the step size to be 5 degrees, then we can make the following table for the steering system.

Degrees	Right Turn				Left Turn			
	a	b	c	T	a	b	c	T
0	1	0	0	0	1	0	0	0
5	0	1	0	1	0	0	1	1
10	0	0	1	0	0	1	0	0
15	1	0	0	1	1	0	0	1
20	0	1	0	0	0	0	1	0
25	0	0	1	1	0	1	0	1

Table - 3

As we can see that some combinations are repeated, which means that we will have to use another flip-flop (say a toggle flip-flop T connected to the clock pulse – this is also indicated in the given table). As the initial value of the flip-flop is fixed and the number of states is odd, the value of T can be used to differentiate between degrees 5 and 20 for e.g.

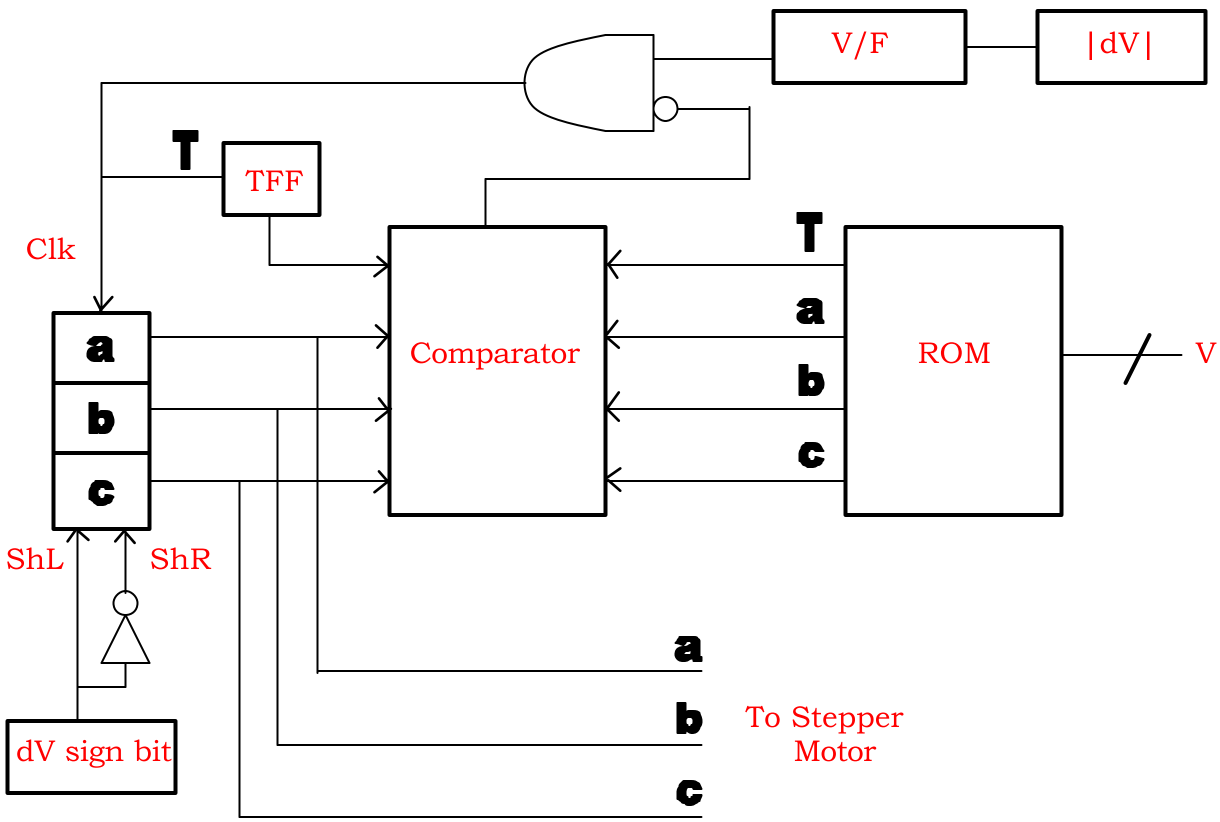
For the circuit implementation of the same we use a 3-bit Ring Counter which is a universal shift register of three bits with the output of the last bit connected to the input of the shift right input and that of the first bit to the shift left input. Thus upon initiation to a value of 1 0 0 (for a, b and c) this works as a perfect output for the stepper motor after proper amplification.

The value of a, b, c and T have to be determined for each value of the output voltage calculated from the V system. For this purpose a ROM is included, the output of which gives the required position of the motor. Thus the motor is made to move according to the sign of the dV system output till the value is same as the output of the ROM.

The clock pulse to the counter comes from a Voltage to frequency converter, the input voltage to which is the magnitude of the dV output stage. This in effect causes the car to steer at a faster rate if it is moving towards an obstruction at a fast rate. This is ANDed with the output from the comparator which goes high when the position of the motor becomes same as the output from the ROM and thus causes the clock pulses to stop.

The direction of motion of the rotor is decided by the sign bit of the dV system output. If the sign is positive, it means that the car needs to be steered more to the right or steering to the left needs to be reduced that implies a shift right in the register. For the negative sign of dV the car either needs to be steered more to the left or the steering to right needs to be reduced that implies a shift left input to the counter.

THE OUTPUT STAGE



Behavior under Different Conditions

Following are the pictorial representations of the behavior of the self maneuvering vehicle under different situations.

- **No objects on any side (within sensing range)**

  If there are no objects on either side within the sensing range, then both E_L and E_R will be zero causing V (output from the V) system to become zero. Under this condition the vehicle will keep going straight till some object comes to within the sensing range.

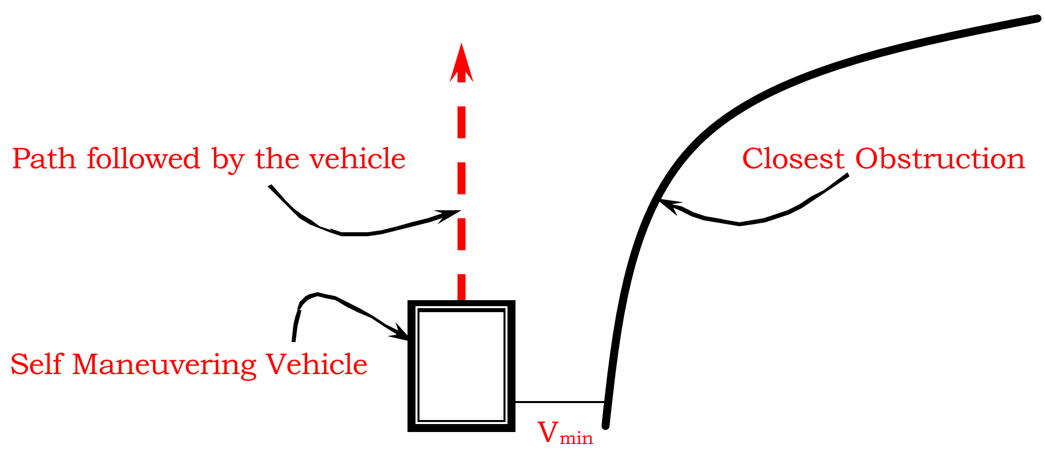
- **Object on one side only**

  If there is an object on one side, then the corresponding E_L or E_R will get enabled. This shall result in the vehicle moving away from the object till the minimum safe distance (decided by the preset voltage V_O) is reached. The dV system makes sure the vehicle doesn't turn away from the initial direction of movement.

  Suppose there is a wall on one side of the vehicle, and the vehicle is maintaining the minimum safe distance. There are two possible situations, i.e. the wall turning away, or turning towards the vehicle.

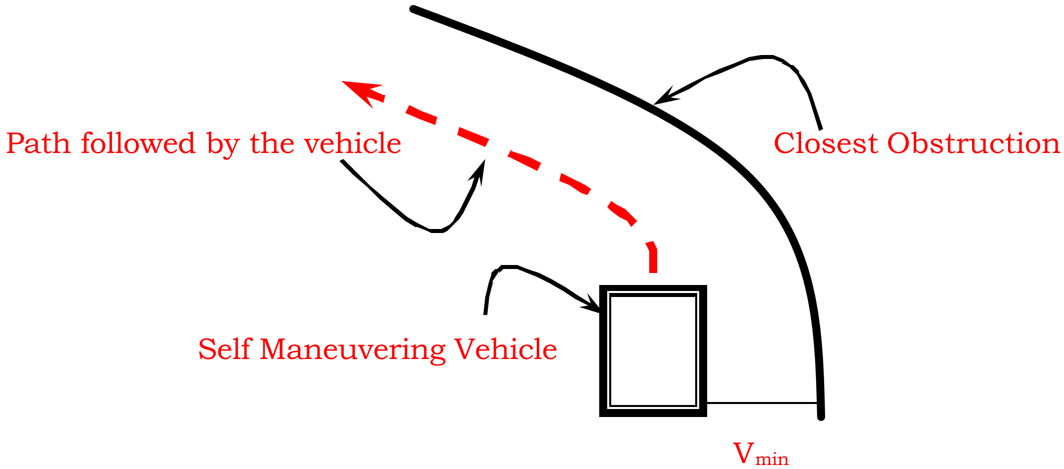
- **Turning away**

  The value of dV will be negative and the value of the V system output is zero (since it is maintaining the safe distance). Thus the comparator output (refer output stage) will be one, and thus no clock pulses shall be given to the counter. This means the vehicle will not turn with the wall, and keep going in the initial direction.



- **Turning towards**

  The value of dV will be positive, and the V system output will have a finite value. Thus the vehicle will try and turn with the wall. If the turn is very sharp, the magnitude of the dV system will be very high, thus the clock pulses to the counter will be faster, hence resulting in faster steering, and avoidance of a collision.



- **Objects on both sides**
  In this case, both E_L and E_R will be activated, resulting in the output of V system being proportional to the difference of the distances from the objects. Thus the vehicle will try and steer itself till the output of the V system is zero, i.e. when the vehicle is equi-distant from both the objects. The dV system makes sure the vehicle keep moving in the initial direction.