

DEVELOPMENT OF STAIR CLIMBING TRANSPORTER

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Abstract

The 'Service Robots' is the area which integrates the technology in the interdisciplinary fields like mechanisms, sensors, electronic control systems, and artificial intelligence. We have developed a stair-climbing transporter (a robot) to carry or transport the loads up or down the stair case. The main features of the transporter include the supporting frame, tilt switch to adjust the angle of the platform, and wheels with triangular belt attached. We are developing the mechanism of SCT further by interfacing it with the popular 89V51RD2 microcontroller to make it an autonomous vehicle with decision making abilities.

Keywords: SCT, Tilt Switches, Microcontrollers

1. Introduction

A mechanism is a combination of rigid or restraining bodies so shaped and connected that they move upon each other with definite relative motion. A machine is a collection of mechanisms which transmits force from the source of power to the load to be overcome, and thus performs useful mechanical work.

Robotics is the area of automation which integrates the technology in variegated fields like mechanisms, sensors & electronic control systems, artificial intelligence and embedded systems. The synthesis of mechanisms is the very first step in any robot design depending upon its application.

1.1 Automation & Robotics Projects

The thrust area of our research work is automation and robotics. Our institute has undertaken many projects in the thrust area of Automation & Robotics. One such project was 'Computer aided design & Interfacing of EOT crane' for remote handling in the hazardous environment in the organizations like BARC. The computer aided design was mainly focused on Snatch Block Assembly and Hoisting Mechanism. The software developed was a tool that provides a universal design solution of the three mechanisms, for different capacity specifications of EOT cranes.

Also it gives a wide range of options for tonnage required and selection of materials, assisting the designer for step by step evaluation of engineering design parameters. The electronic motion control of the crane is achieved by interfacing a fabricated model of EOT crane to the computer through a simple electronic circuit, consisting of Relays & optoisolators. "[1]"

In the area of robotics we are successful in developing two robots. The first one is Shrimp inspired rover with extended climbing ability as shown in Fig.(1). In this project we present an innovative design for a robot with similar climbing ability as the shrimp robot but with 5 wheels.

In the Shrimp robot the sixth wheel was used to maintain balance and achieve greater maneuverability. In our robot we have achieved stability by using suitable dimensions for the fifth wheel. The robot requires minimum control while climbing obstacles as it is able to do so passively.

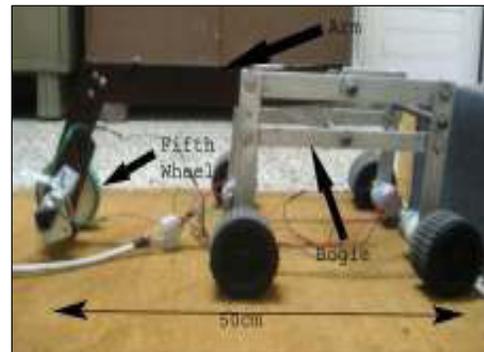


Figure 1: Shrimp Inspired rover

A well-functioning prototype was designed and manufactured in our lab. It shows excellent performance which surpasses our expectations. The robot is able to overcome obstacles of size more than two times its wheel diameter. This robot is a perfect candidate for long range planetary missions as well as for structured and unstructured terrain. The terrestrial applications are also tremendous like indoor and outdoor surveillance, ventilating shaft cleaning, mining and construction machines, agriculture, post earthquake assistance or even mine clearance with the integration of appropriate reliable sensors. "[2]"

Another wall climbing robot developed which was named VHST(Vertical and Horizontal Surface Traverse)as shown in Fig.(2).The project involved design of a wall climbing robot which has versatile wall traversing abilities with sufficient payload capacity. The robot uses a motor-impeller suction cup arrangement to produce the adhesive force against wall and a separate microcontroller system for translation. The concept of direct suction was used. The air is sucked from the underbelly of the robot and thrown out instead of recirculation.

The gap between the wall and the cup would be virtually sealed by a soft material film which conforms to the shape

of the wall in case of small irregularities this helps maintain the drop in pressure. “[3]”

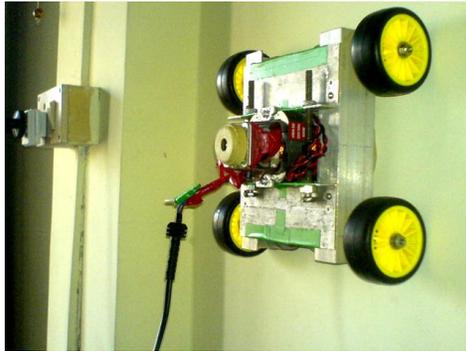


Figure 2: Vertical & Horizontal Traverse (VHST)

1.2 Stair Climbing Transporter (SCT)

The need for the design and development of Stair Climbing Transporter (SCT) emerged from the requirement of an automatic material handling unit for the new set up of the company AIR INDIA.

The delicate aircraft components get damaged by frequent man handling hence we have a proposal to develop an autonomous unmanned vehicle for the transportation of the components from one workstation to another. It not only runs on unstructured terrain with irregular level surfaces but goes another step forward in climbing the staircase up and down.

1.3 The concept

The main purpose of this stair-climbing transporter is to carry or transport loads up or down a stair case. Similar to our project a stair climbing transporter was designed by Polytechnic University (Department of Mechanical Engineering), Brooklyn, NY. There were major modifications required in the project done in the past. The design chosen by us was not one of the designs that were found in the past research. The major limitations of their project done and our respective modifications are as follows.

- i) The earlier designers used a high speed AC motor drive and the motor's rpm was reduced to the desired speed using a worm gear, bevel gear and sprockets inside a gear box. We have used DC motor which has advantages like high starting torque, constant speed, low rpm with better speed control & easy starting.
- ii) We have used alternative gear reduction which eliminate the transmission power loss and increase in the weight of the system. The DC motor selected comes with inbuilt gear reduction allowing the speed reduction ratio of 250 from 5000 rpm to 20 rpm
- iii) Instead of only back wheel drive, we have employed independent four wheel drives. We have provided four motors for each wheel empowering the SCT to overcome the obstacles in a much easier way. This also removed the problem of slipping and non uniform motion caused by chain drive power transmission from back wheels to front wheels.

- iv) Also we have used readily available round belts which give better grip & support. The material used for the wheels is aluminum for its durability, strength and lightening weight of the system.

2. Design Methodology:

The various design aspects of the stair climbing transporter are

- The triangular wheel design
- Drive mechanism to transmit power from Motor
- The Force Analysis
- Control circuit for Platform balancing
- Interfacing with iBoard 8051 for making it autonomous unmanned vehicle
- AI Algorithm for virtual imaging of the terrain

The methodology used during the course of the development of the robot was based on the experiments performed in desired condition, previous experiences, mechanics and trial and error. The initial fabrication has been done based on mechanical design calculations.

2.1 Design of Wheel Geometry

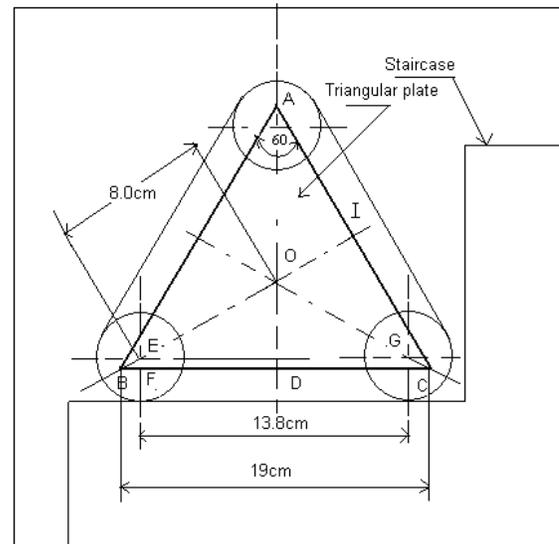


Figure 3: The triangular wheel design based on geometry of the staircase

Assume height of stair = 16cm Pl. Ref. Fig. (3)
 Select side of triangle = 19cm
 Diameter of pulley = 6cm
 Attaching pulley 3cm from vertex
 $BE = CG = 3 \text{ cm}$
 Now $AD = (AB^2 - BD^2)^{1/2}$
 $= (19^2 - 9.5^2)^{1/2}$
 $AD = 16.4 \text{ cm}$

Distance of sprocket center the base $OD = AD/3$
 $OD = 5.5 \text{ cm}$

From triangle BEF
BF = BE Cos30 = 3Cos30 = 2.6cm

Center to center distance of pulley

$$EG = BC - (2*BF)$$

$$EG = 19 - (2*2.6)$$

$$EG = 13.8\text{cm}$$

Center to Center distance of sprocket

$$OE = BI - BE - OI$$

$$OE = 16.45 - 3.0 - 5.5 = 7.95 \text{ cm} = 79.5\text{mm}$$

2.2 Design of chain & belt drive mechanism

The schematic FBD of SCT is shown in Fig. (4).

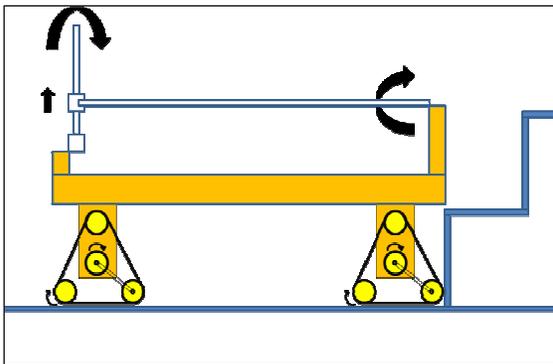


Figure 4: The transmission of power takes place from the DC motor and the chain drive to one pulley & by the belt drive to the other pulleys

We selected the timing chain of Bajaj pulsar having Pitch (p) = 7mm. We had to calculate the length of the chain required so that we could cut the length from the standard chain.

2.2.1 Calculation of length of the chain

Approximate centre distance between two sprockets

$$a = 9.5\text{cm} = 95\text{mm}$$

From PSG data book "[5]"

Length of continuous chain in multiples of pitches

The approximate no of links

$$L_p = 2*Ap + (z1+z2)/2 + [(z1-z2)/2*3.14]^2 / Ap \quad (1)$$

$$\text{Where } Ap = a / p = 80 / 7 = 11.43 \text{ mm}$$

$$Z1 = \text{no of teeth on driver sprocket} = 14$$

$$Z2 = \text{no of teeth on driver sprocket} = 14$$

$$\text{Hence } L_p = 2*11.43 + (14+14)/2 + 0 = 36.86 = 37$$

$$\text{Length of chain} = L_p * p = 37*7 = 259 \text{ mm} = 25.9 \text{ cm} \\ = 26\text{cm}$$

$$\text{Final center distance } A = [e + \sqrt{(e^2 - 8M)*p}] / 4 \quad (2)$$

$$\text{Where } e = L_p - (z1+z2)/2$$

$$= 37 - (14+14)/2 = 23$$

$$M = ((z2-z1)/2*3.14)^2 = 0$$

$$A = (23 + 23)*7/4 = 80.5 \text{ mm}$$

Center distance allowance to accommodate initial slag

$$\text{From PSG } \Delta = 0.5 * f \text{ Where } f = 0.022 * A$$

$$= 0.022 * 80.5 = 1.61$$

Final center distance for sprocket = A - Δ

$$= 80.5 - 1.61 = 78.89 \text{ mm}$$

2.2.2 Calculation of length of belt required

From geometry of wheel

$$\text{Length} = (3 * \text{Center Distance EG}) + (3 * \text{length of arc}) \quad (3)$$

Length of arc = r*θ

$$= 3 * 120 * 3.14 / 180 = 6.283 \text{ cm}$$

$$\text{Length of belt} = (3 * 13.8) + (3 * 6.283) = 60.23 \text{ cm}$$

For maintaining initial tension in the belt reducing belt length by 1%

$$\text{Final length} = 0.99 * 60.23 = 59.62 \text{ cm} = 596.2\text{mm}$$

2.2.3 Belt Tension calculation

Let Co-efficient of friction between pulley and belt be

$$\mu = 0.25$$

Angle of overlap = θ = 120° = 2.094 rad,

N=20 rpm due to inbuilt gear reduction

$$\text{From basic formula } T1/T2 = e^{(\mu*\theta)} \quad (4)$$

$$= e^{(0.25 * 2.094)} = 1.688$$

$$T1 - T2 = P/V \quad (5)$$

Where P = power of driving shaft = 36 W (PI refer 2.3)

$$V = \text{velocity of belt} = (3.14 * 60 * 20) / (60 * 1000)$$

$$V = 0.0628\text{m/s}$$

$$T1 - T2 = 36 / 0.0628 = 573.24$$

Solving equation 4 & 5

$$\text{The tension in the Belt } T1 = 1406.45 \text{ N}$$

$$T2 = 833.21 \text{ N}$$

Accordingly we recommend V belt of A 23 section over each wheel with length 600mm.

2.3 Force Analysis

Weight of each wheel = 1.5 Kg

Weight of four wheels = 6 Kg

Weight of frame and tray = 2 Kg

Assume weight to be transported = 10 Kg

Total weight of the unit (approx) = 18 Kg

Weight to be carried by each wheel = 4.5 Kg

Selecting a DC motor of ratings

Voltage = 12V with 5000 rpm and 3 A Current

Now, Rated Power = V * I

$$= 12 * 3 = 36\text{W}$$

$$P = \frac{2\pi NT}{60} \quad (6)$$

The purpose of this primary force evaluation is to investigate two points as given below.

2.3.1 Turning Moment against point Q

As shown in Fig. (5) we first checked whether the triangular wheel on obstruction at the stair turns or not.

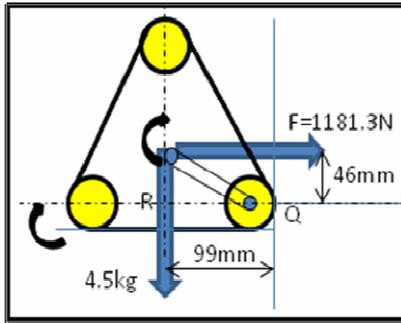


Figure 5: FBD of the wheel, F is the net forward force acting on the wheel while climbing in horizontal direction

Output speed at gear box shaft is $N_2 = N_1 / 250 = 20$ rpm

Therefore, Torque at the pulley of the wheel

$$T = P \cdot 60 / (2\pi N_2)$$

Therefore, $T = 36 \cdot 60 / (2\pi \cdot 20) = 17.19$ Nm

Reaction by each of the two wheels in one triangular wheel,

$$R_1 = R/2 = 4.5/2 = 2.25 \text{ kg}$$

Assuming the coefficient of friction between one wheel and ground as $\mu = 0.4$

Maximum friction force, $F_{\max} = \mu \cdot R_1$ (7)

Therefore, $F_{\max} = 0.4 \cdot 2.25 \cdot 9.81 = 8.829$ N in right side

Force acting due to torque given by motor,

$$F_{\text{motor}} = T/r = 17.19/0.03 = 573 \text{ Nm}$$

Thus total Horizontal force acting on a single triangular wheel

$$F_w = (F_{\max} \cdot 2) + F_{\text{motor}} \quad (8)$$

$$F_w = (8.829 \cdot 2) + 573 = 590.65 \text{ N}$$

The total forward force on each of the front triangular wheels,

$$FF = 2 \cdot F_w = 1181.3 \text{ N}$$

Thus rotating torque in clockwise direction about point Q,

$$T_{\text{rot}} = FF \cdot QP \quad (9)$$

$$T_{\text{rot}} = 1181.3 \cdot 0.046 = 54.33 \text{ Nm (Clockwise)}$$

When the wheel tends to rotate about Q, surface contact will tend to break thus normal reaction at ground is zero.

Turning moment at point Q due to resisting weight

$$T_{\text{res}} = (W/4) \cdot QR \quad (10)$$

$$T_{\text{res}} = (4.5 \cdot 9.81) \cdot 0.099 = 4.37 \text{ Nm (Anticlockwise)}$$

Thus net Rotating Torque per wheel

$$T_{\text{rot}} - T_{\text{res}} = 54.33 - 4.37 = 49.96 \text{ Nm (Clockwise)}$$

As the rotational torque is greater than resisting torque the wheels should turn in clockwise direction about point Q.

2.3.2 Net Force in upward direction

As shown in Fig. (6), we checked whether the triangular wheel experience a net force in the vertical direction

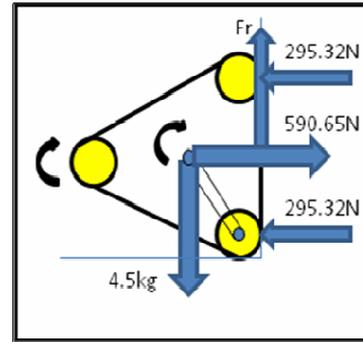


Figure 6: FBD on the verge of rotating about Q

As front wheels climb up, horizontal forward force will be provided by two back wheels only equals to $2 \cdot F_w$. Thus the reaction on each of the two smaller pulleys of one triangular wheel, $R = 590.65/2 = 295.32$ N towards left

Frictional force $F_r = 2(\mu \cdot R) = 2(0.4 \cdot 295.32) = 236.26$ N

Now downward force due to the weight

$$W = 4.5 \cdot 9.81 = 44.15 \text{ N (negative)}$$

Thus, net vertical force on wheel = $F_r - W$

$$= 236.32 - 44.15 = 192.11 \text{ N}$$

As the net vertical force is directing upwards and non zero, we confirm that the wheel will climb. Thus the wheel will get lifted from the ground to climb the vertical surface.

2.4 Control circuit for Platform balancing

As shown in Fig.(7), the tilt switches controlled the raising and lowering of the platform. These are switches that turn on and off at certain angles. There is liquid mercury (metal conductor) inside the tilt switch that is free to move inside a glass tube.

As the switch is turned on, the current flows through the switch. The operating angle of the ON/OFF control is controlled by the mercury level in the tilt switch.

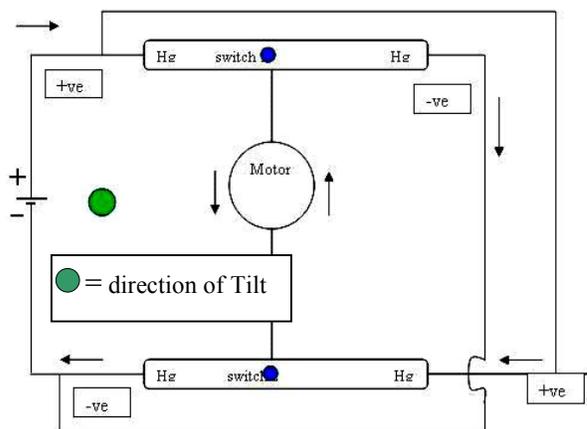


Figure 7: The control circuit for angular position control

In the control circuit two tilt switches were used. They were given opposite polarities of the battery. Both switches were attached to the platform. While climbing the stairs the platform goes down from horizontal position and the mercury in the switches move towards left and the motor get connected to +ve terminal of first switch & -ve terminal of the second. Hence the motor rotates in clockwise direction. The motor rotates the screw rod and hence elevate the platform in horizontal plane.

When the platform goes up from horizontal position while climbing down and the mercury in the switches move towards right and the motor gets connected to -ve end of switch 1 & +ve end of switch 2. Hence the motor rotates in anti-clockwise direction. The motor rotates the screw rod and lower the platform back to horizontal position.

3. Manufacturing Of The SCT

The main features of the transporter included the supporting frame, tilt switches to adjust the angle of the platform and triangular plate with the pulleys and three O rings. The use of the belts with pulleys allows the transporter to go up the stairs due to the friction with the surface of the stairs. The solid model was prepared in ProE as shown in Fig. (8)

The design had four sets of triangular wheels as shown in Fig. (9). The pulleys used in the wheels were with 3 cm diameter. The wheels were chain driven. The chain was wound around the driving sprocket located at the centroid of the triangular plate and the driven sprocket was fixed at the center of one of the pulleys.

The supporting frame was designed to support all the essential parts of the transporter. The motor drive, driven shafts, chains and the platform all were attached to the supporting frame. The tilt switches helped to control the motor that turns the screw rod. This motor rotated a screw rod that raised or lowered the angle of the platform until the desired tilt angle of 0° degrees was obtained. This kept the platform always parallel to the ground.

Before the actual fabrication begun, a plan was laid out. The fabrication was done in two stages

- The manufacture of wheels and chassis
- The platform mechanism and electronics

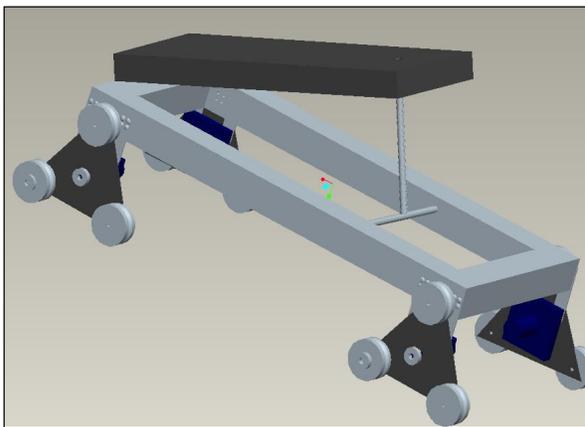


Figure 8: The Solid Model of SCT in PRO-E to get better understanding of the assembly of different components



Figure 9: The Triangular Wheel gives the SCT an ability to climb up the stairs

3.1 Why Triangular wheel

The design for the wheels was done according to the average width and height of a stair. Once the design was finalized, the material for the wheel was selected. It was decided to use aluminum for the triangular plate and pulleys due to its durability, strength and light weight.

The pulleys were fabricated according to standard rubber pulleys that were available in the market. Once the pulleys and the plates were made, holes were drilled in the plates. Bushes were attached to the plate so that the pulleys would rotate freely.

Next, the sprockets were added to the assembly. The driving sprockets were attached to the motor shaft through a bush and Allen screws. The driven sprockets were press fitted to one pulley on each wheel. The deep groove ball bearings were selected to allow for free wheeling of the triangular plates. The bearing housings were also made to accommodate the bearing. Utmost care was taken for the alignment of the various driving mechanisms viz. chain drive & belt drive for the wheels.

3.2 Manufacture of frame and Links

The frame was made of aluminum box section of size 8x4 sq. cm. Four hollow pieces were connected together with screws to form a rigid structure. To attach the motors and the wheels to the frame, supporting frames were made using thin aluminum strips. The length of each frame was decided upon taking into consideration the height of the stair and the amount of clearance necessary to keep the frame from coming in contact with it.

As we were manufacturing a working model to save cost we have used an acrylic sheet of four millimeters thickness and area 30x60 sq. mm for the platform. It is hinged to the main frame on one edge. On the other edge it rests on a screw rod.

The screw rod was driven by a motor which was coupled to it. The nut was fitted into the platform through which the screw rotated and the platform was raised up or down.

4. Testing & Modifications

As shown in Fig. (10), in the preliminary testing the SCT was tested to study its performance and following modifications were made.



Figure 10: Stair climbing transporter in testing process

- i) Metallic sprockets were selected with well defined teeth to mesh perfectly with the chain and not cause slip.
- ii) Deep groove ball bearings were placed at the centroid of each wheel in housing for free wheeling of the plate when traveling over the stair.
- iii) The rubber belts were replaced with high tension O-rings that can withstand a maximum load of 10kg. Once the modifications were made, the transporter was again tested along with the satisfactory functioning of the platform.
- iv) To accommodate the O-rings, the pulleys were modified. Instead of just one groove in the pulley, three grooves were made to wrap three O-rings of tensile strength 10Mpa. This was done to provide adequate tension in the O-rings.

5. Development of SCT as an AGV

We have decided to use an iBoard with 8051 microcontroller developed by TRI Techno solutions Pvt. Ltd. to solve the problem of automatic navigation of our robot.

It has two ports, one for driving the motors and another port with eight pins to connect the output of the sensors. The board can drive a maximum of 4 DC bidirectional motors. To add on more motors we have to use additional motor driver cards namely mosfet motor driver.

This 8051 microcontroller based development board as shown in Fig. (12) is ideal for making autonomous robots, course projects, generic embedded system applications etc. This compact board has motor drivers, LEDs, switches, LCD display, in system programming facility and sensor connectors.

We have tested these boards for various programs done in C language at Mechatronics lab, IIT (Bombay). The flowcharts are shown in Fig. (11) & (13). We have practically tested this iBoard for obstacle sensing and line follower algorithm.

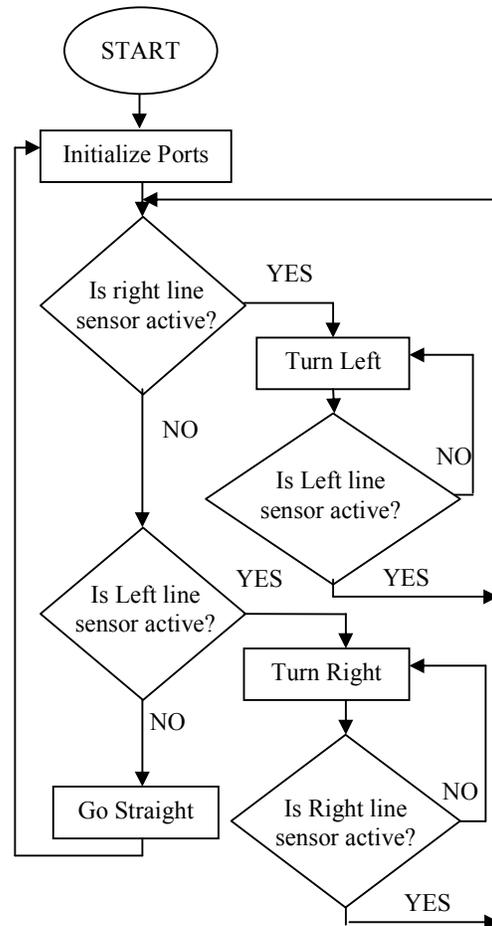


Figure 11: Block diagram for Line following algorithm

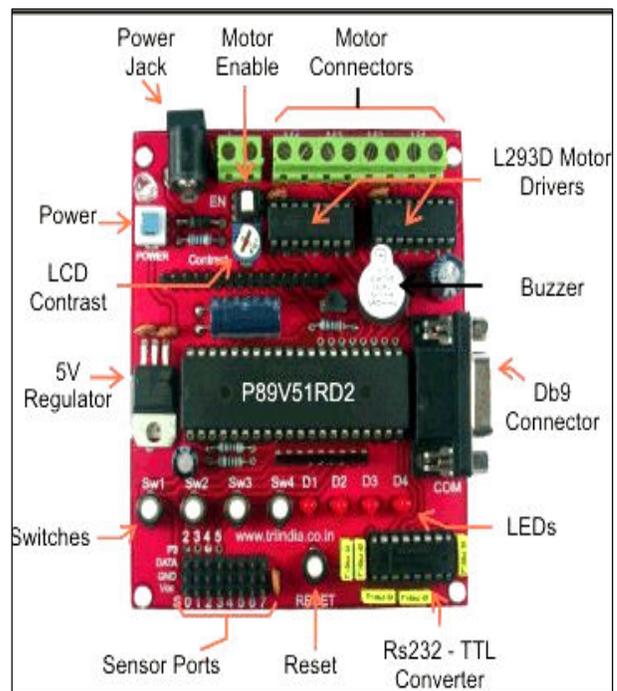


Figure 12: The 8051_iBoard to control the SCT Navigation

The iBoard specifications are as follows. It contains Philips 89V51RD2 microcontroller with 64kB flash memory working at 11.0592MHz. Also it has a built in ISP (In System Programming) circuit.

The iBoard is provided with RS232-TTL level converter with 40 pin IC base for compatible PDIP microcontroller packages. The company provides a compiler where we can compile the program in C and feed it to the controller through this port. We have successfully programmed this board for various functions like line follower, obstacle detection and found it to be highly effective.

This iBoard operates on a wide range of voltages from 7V-15V. It has two on board dual full H bridge motor driver for 2 stepper or 4 DC motors. The current is 600mA per channel of motors. There is a separate ON/OFF switch for power and motor drivers. It has 8 bit port for sensor connections on board with UART communication circuit with the computer. Thus we can connect the sensors output to the microcontroller port and according to our requirement program the robot.

5.1 The Sensors

We are using two sensors developed by TRI Techno solutions Pvt. Ltd. They are IR sensors for obstacle detection & ultrasonic sensors for distance measurement.

5.1.1 Infrared line sensor

This general purpose IR Transmitter Receiver sensor is ideal for line detection. It allows the robot to move on a terrain along a line that signifies a predefined path. The sensor has an IR transmitter and a receiver. An infrared LED is paired with an infrared photodiode or phototransistor that acts like a detector. We have decided use two such sensors to make the robot to follow a line.

5.1.2 TSOP based obstacle detector module

The obstacle detection sensors mounted on left & right side of the robot to empower it with the decision making ability to turn right or left respectively when there is an obstacle.

An infrared LED is paired with an infrared photodiode or phototransistor. Based on the intensity of the reflected signal the obstacle is detected. The output is active low and toggles between 0-5V. That means when the infrared light detects any surface the LED glows, otherwise it is off.

5.2 AI Algorithm for tracing the map of the terrain

5.2.1 Level I: Let's assume that the robot is placed in a room and the room is empty with the door. The aim of the algorithm with level I is to enable the robot to maneuver out of the room of its own. We have decided to mount an ultrasonic sensor shown in Fig (14) on a rotary disc, driven by a stepper motor. The sensor output will be the distance of the wall from the robot which will be fed to microcontroller. The sensor gives a digital signal proportional to the distance of the obstacle. This signal is fed to 8051 microcontroller to process it as needed.

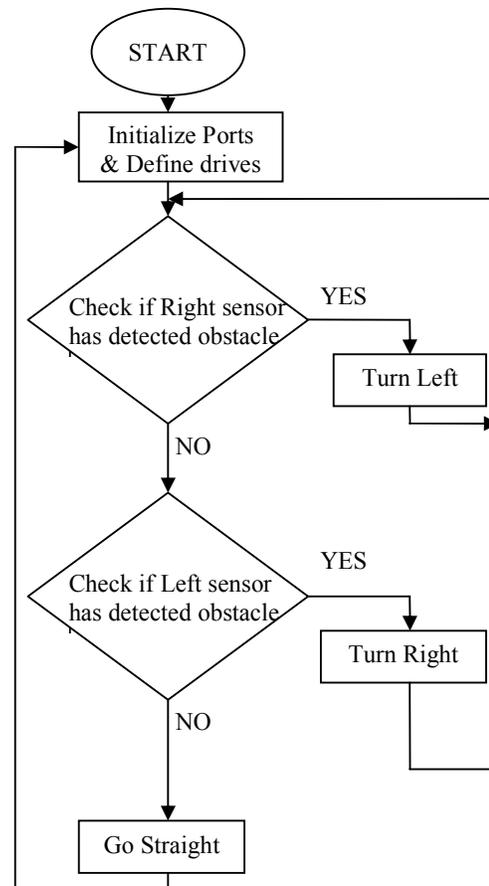


Figure 13: Block diagram for obstacle avoiding robot

The number of pulses given to stepper motor with minimum angle of turn of 1.8° forms the basis of angle measurement for the distance traced by the ultrasonic distance measuring unit. We have decided to use Pancake 1.8 deg stepper motor, with rating 9.6V, 20mNm. After this data acquisition the robot generates a series of data with angles and distances of the walls or objects. From this we are able to work out the contour of the wall using software based on the mathematics of curve tracing.

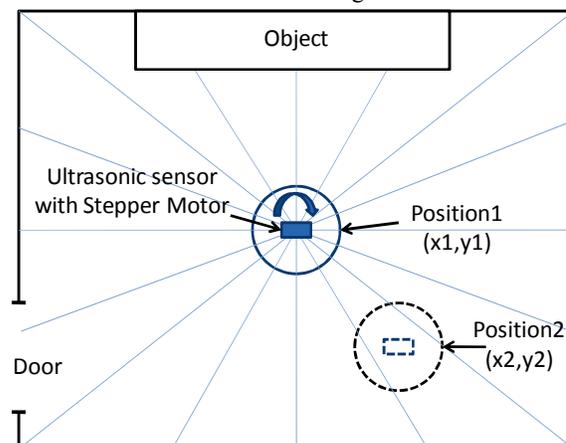


Figure 14: Tracing the map of the room using an Ultrasonic Sensor and a stepper motor. The Sensor rotates in 360° and the distance of the object is measured at an angle recorded by stepper motor.

5.2.2 Level II

As shown in Fig. (14), in level two the data acquisition takes place at different locations depending upon the room layout or objects. We will graphically plot the layout of the room using three inputs

- a. The coordinate of robot position
- b. The angle of the sensor at each position with respect to wall object
- c. The distance of the object

From these three inputs fed to computer program we should be able to plot the contour or the layout of the room.

6. Results & Discussion

On testing the robot we observed following limitations on which presently we are working

1. The round belts used are in direct contact to the ground and hence wear up faster.
2. Every wheel has two contact points. Turning the robot left or right causes the wheels to slide along the ground.
3. There is no adequate place (unless designed) to put the batteries and electronic circuit required to make the vehicle autonomous.
4. The response time for horizontal balancing of the platform needs to be enhanced
5. Also the speed of the robot is constant which needs to be variable i.e. slow on stairs and fast on level ground.

6.1 Rectifications planned

1. We are trying to make an alternative design for the triangular wheel in which the belts can be removed
2. In the new design, the wheels are in direct contact with the ground. Hence better steering is possible without scabbing.
3. The rectangular frame of the robot is to be changed to C section type in which the upper flange can be used to mount platform and lower one can be used for mounting the circuits and batteries.
4. The screw rod that was used in the earlier designed is redesigned with more number of starts to reduce the response time.
5. A variable speed motor is to be used to control the SCT

7. Future Scope

The major challenges for our researchers in the future are as follows

- a. To redesign and manufacture a working model of SCT to carry a load of 50 Kg to suit the application at AIR INDIA for material handling
- b. To develop mechanisms to reduce the jerks and add more strength to the machine components
- c. FE analysis for the SCT as a whole avoiding any unforeseen failures of the components
- d. Develop software for maneuvering using AI for tracing the path of the terrain.

8. Conclusions

In this paper we have suggested the development of innovative product of stair climbing transporter. The attempt of making SCT as an AGV is successful and practically more significant. The design of SCT with the techniques of artificial intelligence to trace map the terrain will be the area of our next paper.

9. Acknowledgments

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