Biped Patrol

Task 3.3: Think & Answer

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Question No.	Max. Marks	Marks Scored
Q1	10	
Q2	20	
Q3	5	
Q4	5	
Q5	5	
Q6	10	
Q7	15	
Q8	8	
Q9	4	
Q10	8	
Q11	10	
Total	100	

Biped Patrol

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Instructions:

- There are no negative marks.
- Unnecessary explanation will lead to less marks even if answer is correct.
- If required, draw the image in a paper with proper explanation and add the snapshot in your corresponding answer.

Q 1. Describe hardware design for the Medbot, your team is constructing. Describe various parts with well labeled image. Give reasons for selection of design. [10]

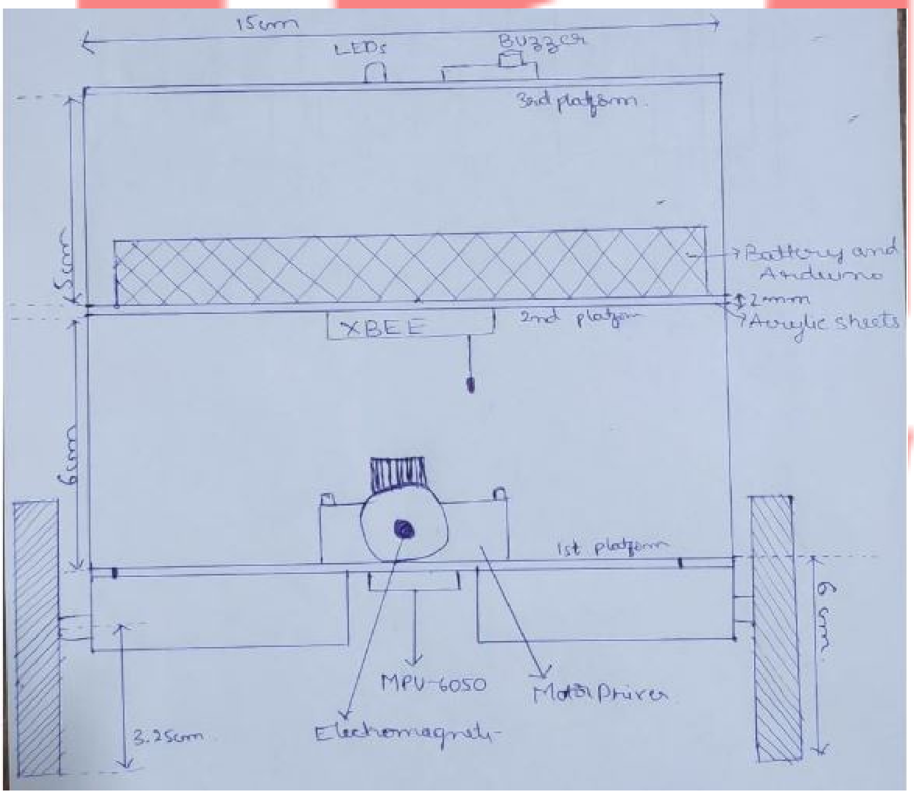

Figure 1: Side view of the medbot

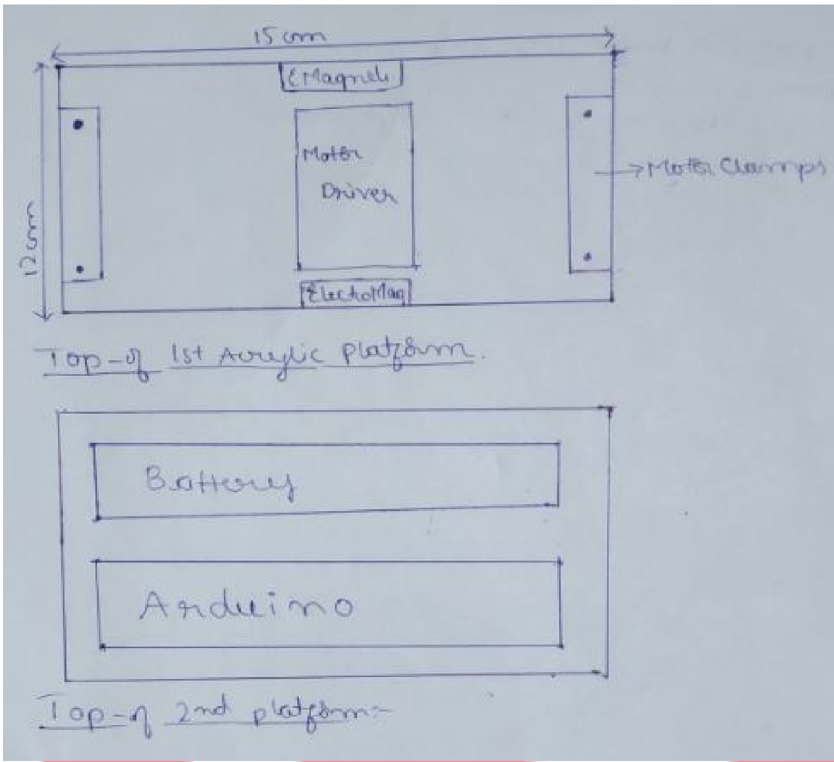

Figure 2: Top view of the medbot

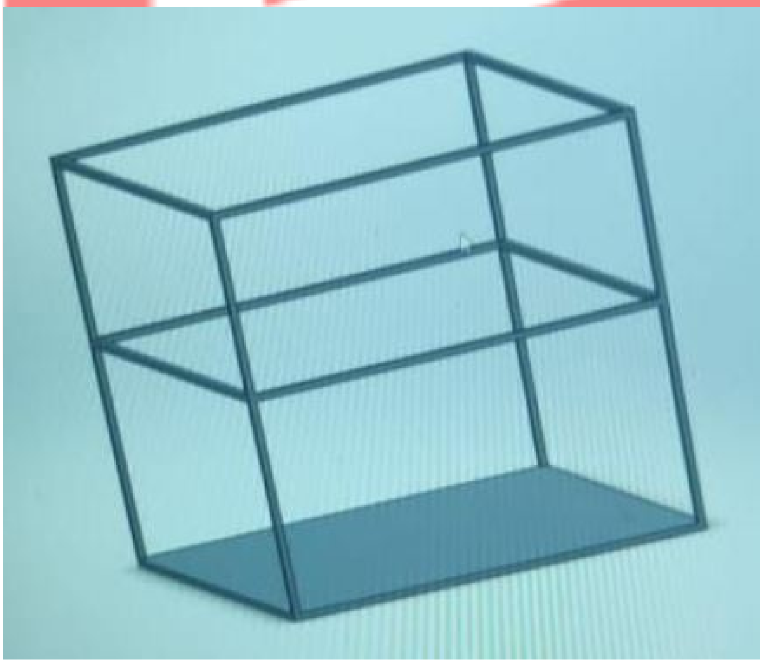

Figure 3: The structure of medbot

A 1. We are using 3 acrylic sheets (2mm) with dimension 15cm*12cm. 1st and 2nd is seperated with studs of length 6cm, 2nd and 3rd is seperated with studs of length 5cm. At the bottom of 1st sheet motor clamps(fixed to motor) are placed(at the ends of the sheet) between the motors MPU-6050 is placed and on top of 1st sheet motor driver is placed (in the middle part of the sheet) and it is surrounded by electromagnets(placed at the horizontal edge) At the bottom of 2nd sheet XBEE is placed and Battery and Arduino are placed on the top side of it. On top of the 3rd platform buzzer and leds are placed.
Battery is placed on the top of second platform so that Centre Of Mass is far from the axle as it contains more mass compared to other components. IMU sensor is placed at the bottom of 1st platform so that it stays near to axle, as if it is placed far from axle there are chances of sensor getting saturated. Horizontal Width of the platform is chosen to be 15cm so that IMU(2cm) sensor can be placed between encoder motors(6cm each). Vertical width of the platform is chosen to be 12 cm so that we can place arduino and battery side by side.

Q 2. In Task 1.2, you were asked to model different systems such as Simple Pulley, Complex Pulley, Inverted Pendulum with and without input and stabilizing the unstable equilibrium point using Pole Placement and LQR control techniques. There you had to choose the states; Derive the equations (usually non-linear), find equilibrium points and then linearize around the equilibrium points. You were asked to find out the linear system represented in the form

$$\dot{X}(t) = AX(t) + BU(t) \tag{1}$$

Where $X(t)$ is a vector of all the state,i.e., $X(t) = [x_1(t), x_2(t), \ldots, x_n(t)]^T$, and $U(t)$ is the vector of input to the system, i.e. $U(t) = [u_1(t), u_2(t), \ldots, u_m(t)]^T$. A is the State Matrix & B is the Input Matrix.

In this question, you have to choose the states for the Medbot you are going to design. Model the system by finding out the equations governing the dynamics of the system using Euler-Lagrange Mechanics. Linearize the system via Jacobians around the equilibrium points representing your physical model in the form given in equation 1.
Note: You may choose symbolic representation such as M_w for Mass of wheel, etc. [20]

A 2. The terms in the figure 4 are:
M_w = mass of wheel
M_r = mass of rod
I_w = Inertia of wheel
I_r = Inertia of rod
τ = torque from motors
R = radius of wheel
L = length from end to center of mass of the rotating body
g = gravity (9.81 m/s)

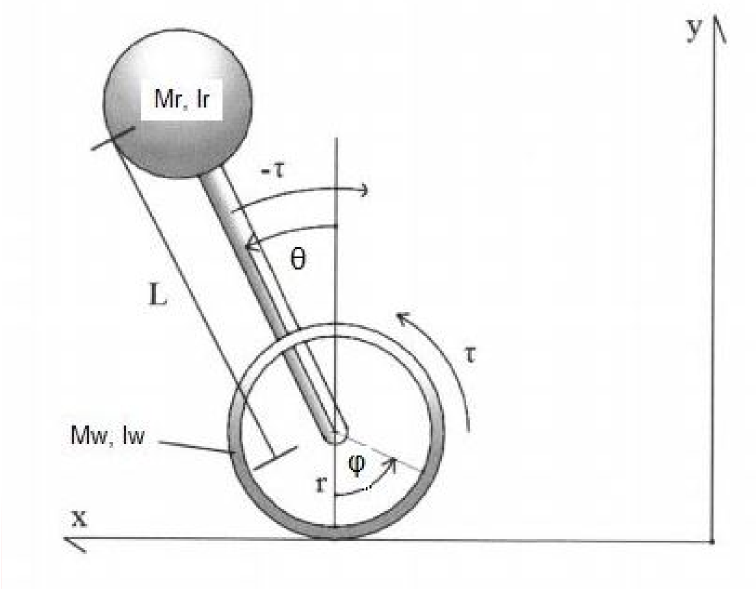

Figure 4: Basic Medbot with wheel and rod

From parallel axis theorem, moment of inertia about axle of the wheel $I = [I_w + M_w R^2]$

$$K.E = \frac{1}{2}[I_w + M_w R^2]\dot{\phi}^2 + \frac{1}{2}[I_r\dot{\theta}^2] + \frac{M_r}{2}[(L\dot{\theta})^2 + (R\dot{\phi})^2 + 2RL\dot{\theta}\dot{\phi}cos\theta] \tag{2}$$

$$K.E = \frac{\dot{\phi}^2}{2}[I_w + M_w R^2 + M_r R^2] + \frac{\dot{\theta}^2}{2}[I_r + M_r L^2] + M_r RL\dot{\theta}\dot{\phi}cos\theta \tag{3}$$

$$P.E = M_r gLcos\theta \tag{4}$$

Langragian $L = K.E - P.E = \frac{\dot{\phi}^2}{2}[I_w + M_w R^2 + M_r R^2] + \frac{\dot{\theta}^2}{2}[I_r + M_r L^2] + M_r RL\dot{\theta}\dot{\phi}cos\theta - M_r gLcos\theta$

From Langragian-euler method

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\theta}}) - \frac{\partial L}{\partial \theta} = Q_\theta \tag{5}$$

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\phi}}) - \frac{\partial L}{\partial \phi} = Q_\phi \tag{6}$$

$\frac{\partial L}{\partial \dot{\theta}} = [I_r + M_r L^2]\dot{\theta} + M_r RL\dot{\phi}cos\theta$

$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\theta}}) = [I_r + M_r L^2]\ddot{\theta} + M_r RL\ddot{\phi}cos\theta - M_r LR\dot{\theta}\dot{\phi}sin\theta$

$\frac{\partial L}{\partial \theta} = -M_r Lsin\theta[R\dot{\theta}\dot{\phi} - g]$

$$[I_r + M_rL^2]\ddot{\theta} + M_rRLcos\theta\ddot{\phi} - M_rLgsin\theta = -\tau \tag{7}$$

$\frac{\partial L}{\partial \dot{\phi}} = [I_w + M_wR^2 + M_rR^2]\dot{\phi} + M_rRL\dot{\theta}cos\theta$

$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\phi}}) = [I_w + M_wR^2 + M_rR^2]\ddot{\phi} - M_rRL\dot{\theta}^2sin\theta + (M_rRLcos\theta)\ddot{\theta}$

$\frac{\partial L}{\partial \phi} = 0$

$$[I_w + (M_w + M_r)R^2]\ddot{\phi} + (M_rRLcos\theta)\ddot{\theta} - M_rRL\dot{\theta}^2sin\theta = \tau \tag{8}$$

$$\begin{bmatrix} [I_r + M_rL^2] & M_rRLcos\theta \\ (M_rRLcos\theta) & [I_w + (M_w + M_r)R^2] \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} - \begin{bmatrix} M_rLgsin\theta \\ M_rRL\dot{\theta}^2sin\theta \end{bmatrix} = \begin{bmatrix} -\tau \\ \tau \end{bmatrix} \tag{9}$$

Solving for $\ddot{\theta}$ and $\ddot{\phi}$ from eqn (9) using cramer's rule, we get

$$\ddot{\phi} = \frac{M_rRLsin\theta((I_r + M_rL^2)\dot{\theta}^2 - M_rgLcos\theta)}{\Delta} + \frac{\tau(I_r + M_rL^2 + M_rRLcos\theta)}{\Delta} \tag{10}$$

$$\ddot{\theta} = \frac{-M_rLsin\theta(M_rR^2L\dot{\theta}^2cos\theta - (I_w + (M_w + M_r)R^2)g)}{\Delta} - \frac{\tau(M_rRLcos\theta + I_w + (M_w + M_r)R^2)}{\Delta} \tag{11}$$

Where $\Delta = [I_r + M_rL^2][I_w + (M_w + M_r)R^2] - (M_rRLcos\theta)^2$

Let $x_1 = \theta, x_2 = \dot{\theta}, x_3 = \phi, x_4 = \dot{\phi}, u = \tau$, so that $\dot{x_1} = x_2, \dot{x_3} = x_4, \dot{x_2} = \dot{\dot{\theta}}, \dot{x_4} = \dot{\dot{\phi}}$

We have

$$A = \begin{bmatrix} \frac{\partial \dot{x_1}}{\partial x_1} & \frac{\partial \dot{x_1}}{\partial x_2} & \frac{\partial \dot{x_1}}{\partial x_3} & \frac{\partial \dot{x_1}}{\partial x_4} \\ \frac{\partial \dot{x_2}}{\partial x_1} & \frac{\partial \dot{x_2}}{\partial x_2} & \frac{\partial \dot{x_2}}{\partial x_3} & \frac{\partial \dot{x_2}}{\partial x_4} \\ \frac{\partial \dot{x_3}}{\partial x_1} & \frac{\partial \dot{x_3}}{\partial x_2} & \frac{\partial \dot{x_3}}{\partial x_3} & \frac{\partial \dot{x_3}}{\partial x_4} \\ \frac{\partial \dot{x_4}}{\partial x_1} & \frac{\partial \dot{x_4}}{\partial x_2} & \frac{\partial \dot{x_4}}{\partial x_3} & \frac{\partial \dot{x_4}}{\partial x_4} \end{bmatrix} \tag{12}$$

$$B = \begin{bmatrix} \frac{\partial \dot{x_1}}{\partial u} \\ \frac{\partial \dot{x_2}}{\partial u} \\ \frac{\partial \dot{x_3}}{\partial u} \\ \frac{\partial \dot{x_4}}{\partial u} \end{bmatrix} \tag{13}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ A_{21} & \frac{-2(M_rLR)^2sin\theta\dot{\theta}}{\Delta} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ A_{41} & \frac{2M_rRLsin\theta(I_r+M_rL^2)\dot{\theta}}{\Delta} & 0 & 0 \end{bmatrix} \tag{14}$$

Where,

$$A_{21} = \frac{[[I_r + M_rL^2][I_w + (M_w + M_r)R^2] - (M_rRLcos\theta)^2][\tau M_rRLsin\theta + (I_w + (M_w + M_r)R^2)gM_rLcos\theta}{\Delta^2}$$

$$\frac{-(M_rLR\dot{\theta})^2cos(2\theta)] + [M_rLsin\theta(M_rR^2L\dot{\theta}^2cos\theta - (I_w + (M_w + M_r)R^2)g)}{\Delta^2}$$

$$\frac{\tau[(M_rRLcos\theta) + [I_w + (M_w + M_r)R^2)]][2(M_rRL)^2cos\theta sin\theta]}{\Delta^2}$$

$$A_{41} = \frac{[[I_r + M_rL^2][I_w + (M_w + M_r)R^2] - (M_rRLcos\theta)^2][M_rRLcos\theta((I_r + M_rL^2)\dot{\theta}^2) - (M_rL)^2Rgcos(2\theta)}{\Delta^2}$$

$$\frac{-\tau M_rLRsin\theta] - [M_rRLsin\theta((I_r + M_rL^2)\dot{\theta}^2 - M_rgLcos\theta) + \tau(I_r + M_rL^2 + M_rRLcos\theta)][2(M_rRL)^2cos\theta sin\theta]}{\Delta^2}$$

$$B = \begin{bmatrix} 0 \\ \frac{-(M_rRLcos\theta + I_w + (M_w + M_r)R^2)}{\Delta} \\ 0 \\ \frac{(I_r + M_rL^2 + M_rRLcos\theta)}{\Delta} \end{bmatrix} \tag{15}$$

Substituting equilibrium point (0,0,0,0) to the above equation we get

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{(I_w + (M_w + M_r)R^2)gM_rL}{\Delta_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{-(M_rL)^2Rg}{\Delta_1} & 0 & 0 & 0 \end{bmatrix} \tag{16}$$

$$B = \begin{bmatrix} 0 \\ \frac{-(M_rRL + I_w + (M_w + M_r)R^2)}{\Delta_1} \\ 0 \\ \frac{(I_r + M_rL^2 + M_rRL)}{\Delta_1} \end{bmatrix} \tag{17}$$

Where $\Delta_1 = [I_r + M_rL^2][I_w + (M_w + M_r)R^2] - (M_rRL)^2$

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{(I_w + (M_w + M_r)R^2)gM_rL}{\Delta_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{-(M_rL)^2Rg}{\Delta_1} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{-(M_rRL + I_w + (M_w + M_r)R^2)}{\Delta_1} \\ 0 \\ \frac{(I_r + M_rL^2 + M_rRL)}{\Delta_1} \end{bmatrix} [\tau] \tag{18}$$

Q 3. Equation 1 represents a continuous-time system. The equivalent discrete time system is represented as:

$$X(k+1) = A_d X(k) + B_d U(k) \tag{19}$$

Where $X(k)$ is a measure of the states at k_{th} sampling instant,i.e., $X(k) = [x_1(k), x_2(k), \ldots, x_n(k)]^T$, and $U(k)$ is the vector of input to the system at k_{th} sampling instant, i.e. $U(k) = [u_1(k), u_2(k), \ldots, u_m(k)]^T$. A_d is the Discrete State Matrix & B_d is the Discrete Input Matrix.

What should be the position of eigen values of A_d for system to be stable.
Hint: In frequency domain, continuous-time system is represented with Laplace transform and discrete-time system is represented with Z transform. [5]

A 3. As we know that a discrete time system is represented with Z transform. The given discrete time system can be expressed as follows :
$Y(z) = H(z) * U(z)$
where, H(z) is a transfer function, U(z) is the input function, Y(z) is the output function
We know that for a bounded input condition, for the system response to be stable the poles of H(z) must lie inside a unit circle. Here A_d matrix Eigen values corresponds to the poles of H(z). Therefore when the Eigen values of A_d is plotted in Z plane, the position of it should be inside a unit circle for the system to be stable.

Q 4. Will LQR control always works? If No, then why not? and if Yes, Justify your answer.
Hint: Take a look at definition of Controllable System. What is controllability? [5]

A 4. LQR control can be used only when the system is controllable. Because we want to drive the system from initial state to desired state with certain performance which can be chosen from choosing the value of Q and R matrices. Since we can achieve any desired state only when the system is controllable, we should make sure that the system is controllable before applying LQR control.

Q 5. For balancing robot on two wheel i.e. as inverted pendulum, the center of mass should be made high or low? Justify your answer. [5]

A 5. The center of mass of the system should be made high. This is because it provides more time to control.

Torque= $M_r g sin\theta R$
Moment of Inertia about axle= $I_r + M_r R^2$
$(I_r + M_r R^2)\alpha = M_r g sin\theta R$
$\alpha = (M_r g sin\theta R)/(I_r + M_r R^2)$
Denominator grows faster than Numerator therefore α reduces with increase in R. This reduce

in α provides more time to stabilize the system.

Q 6. Why do we require filter? Do we require both the gyroscope and the accelerometer for measuring the tilt angle of the robot? Why? [10]

A 6. We need filters to eliminate noise in the input. No its not necessary to have both gyroscope and accerlometer to calculate the tilt angle. Readings from only one of the sensors is sufficient to calculate the tilt angles but have their own limitations. Gyroscope is subjected to drift which accumulates overtime which can be removed by passing through high pass filter. Accerlometer has slow response time and contains only low pass signals. High frequency noise can be removed by passing it through the low pass filter. Reading from one can be used to confirm on other. Using complimentary filter we can use both sensors data in their acceptable frequency range and combine them to get better estimate of the input

Q 7. What is Perpendicular and Parallel axis theorem for calculation of Moment of Inertia? Do you require this theorem for modelling the Medbot?Explain Mathematically. [15]

A 7. Perpendicular Axis Theorem: The moment of inertia of a planar body about an axis perpendicular to its plane is equal to the sum of its moments of inertia about two perpendicular axes concurrent with the perpendicular axis and lying in the plane of the body.

Parallel Axis Theorem: The moment of inertia of a body about an axis parallel to an axis passing through the centre of mass is equal to the sum of the moment of inertia of body about an axis passing through centre of mass and product of mass and square of the distance between the two axes.

We require Parallel axis theorem to model the med bot. To find the rotational kinetic energy of wheel(no slip rolling) in the lagrange method(known moment of inertia about centre of mass) we can obtain moment of inertia about the point of contact of wheel with ground using parallel axis theorem.

$$KEofwheel = \frac{1}{2}(I_w + M_r R^2)\dot{\phi}^2$$

Q 8. What will happen in the following situations:

(a) Medbot picks a First-Aid Kit from the shelf of Medical Store but the First-Aid Kit falls inside the store. Will there be any penalty imposed, points awarded? Will the First-Aid Kit be repositioned? [2]

(b) Medbot picks a First-Aid Kit from the shelf of Medical Store but the First-Aid Kit falls outside the store. Will there be any penalty imposed, points awarded? Will the First-Aid Kit be repositioned? [2]

(c) Medbot picks a First-Aid Kit from the shelf of Medical Store but the First-Aid Kit and the Medbot both fall inside the store. Will there be any penalty imposed, points awarded? Will the First-Aid Kit be repositioned? [2]

(d) Medbot picks a First-Aid Kit from the shelf of Medical Store but the First-Aid Kit and the Medbot both fall inside the store. Will there be any penalty imposed, points awarded? Will the First-Aid Kit be repositioned? [2]

A 8. (a) Since the FAK block falls inside the medical store it does not qualify as a successful pickup (M_{PU} is not awarded). If the medbot touches anything other than the items in the medical store then hit penalty (M_{HP}) is given and hence no penalty run (M_{NPR}) is not awarded. The block is not re-positioned.

(b) Since the FAK block falls outside the medical store, it qualifies as a successful pickup (M_{PU} is awarded). If the medbot touches anything other than the items in the medical store then hit penalty (M_{HP}) is given and hence no penalty run (M_{NPR}) is not awarded. The block is not re-positioned.

(c) Since both FAK and medbot falls inside the medical store, it does not qualify as successful pickup (M_{PU} is not awarded). Fall penalty (M_{FP}) is given and if the medbot touches anything other than the items in the medical store then hit penalty (M_{HP}) is given and hence no penalty run (M_{NPR}) is not awarded. Both FAK and medbot are re-positioned.

(d) Since both FAK and medbot falls outside the medical store, it qualify as successful pickup (M_{PU} is awarded). Fall penalty (M_{FP}) is given and if the medbot touches anything other than the items in the medical store then hit penalty (M_{HP}) is given and hence no penalty run (M_{NPR}) is not awarded. Both FAK and medbot are re-positioned.

Q 9. What will be the points awarded if Medbot picks only one of the item from the medical store and repeatedly moves back and forth around the gravel pathway or the bridge for the entire run. [4]

A 9. Given that the medbot has successfully picked up one of the item, M_{PU} is awarded and also ERG is incremented (empty crossing of gravel pathway at start from parking area to medicine store). There are no penalties.

1. If it repeatedly crosses the bridge for the entire run, T=600 as there are no successful run and LRB is incremented each time the medbot crosses the bridge carrying the item.
2. If it repeatedly crosses the gravel pathway for the entire run, T=600 as there are no successful run and LRG is incremented each time the medbot crosses the gravel pathway carrying the item.

Q 10. What are the different communication protocols you'll be using? Name the hardware interfaced related to each of the communication protocols. Explain how these communication protocols works and what are the differences between them. [8]

A 10. The communication protocols used are: I2C, UART, ZIGBEE.
I2C communication protocol is used between arduino mega and GY-87 sensor module.
Working: I2C is a two-wire interface consisting of data line (called SDA) and a clock line (called SCL). I2C makes use of a master-slave model to establish the "hierarchy" of communication(here masters select slaves through their unique byte addresses). The data and clock lines are pulled high in their idle states, and when data needs to be sent over the connection, the lines are pulled low through some MOSFET circuits.On the Arduino, I2C implementation occurs through the Wire library (Wire.h) where it can be configured as either an I2C master or slave device and the byte data is written over the I2C bus.Here both read or write operation is performed on slave.
I2C has the ability to connect multiple masters to multiple slaves. It has high speed communication due to good Synchronicity. Easy implementation as only two wires and some resistors are required.
UART communication protocol is used between arduino mega and Zigbbe module.
Working: It is serial communication with 2 lines(Rx and Tx).The communication does not depend on a synchronized clock signal between the two devices attempting to communicate with each other. The data consists of 1 start bit and 7 bit data and a parity bit and stop bit. As the data is serial, serial in parallel out registers is used.
It is half duplex. It is slower than I2C.
Zigbee communication protocal is used between the 2 Zigbee modules.
Working: It is a wireless sensor network. Here One device is designated as the PAN coordinator which is the responsible for maintaining the network and managing other devices.// It has high networking level (mesh) due to which data loss is minimized when compared to other communication methods

Q 11. Why do we require IRF540N? Provide circuit diagram for interfacing IRF540N with the microcontroller. [5+5]

A 11. The electromagnet we use draws huge amount of current (greater than 500mA) and operates at high voltage of 12v. Since Arduino's I/O pins cannot supply high current, we require a driver circuit that is operated as a switch and controlled by Arduino. We choose n-channel MOSFET IRF540N as a switch and current driver. It has a current rating of 10A at 5v vgs which is a very high value compared to the required current specifications. Also it has low drain-source ON resistance so that there is very less voltage drop across the transistor.

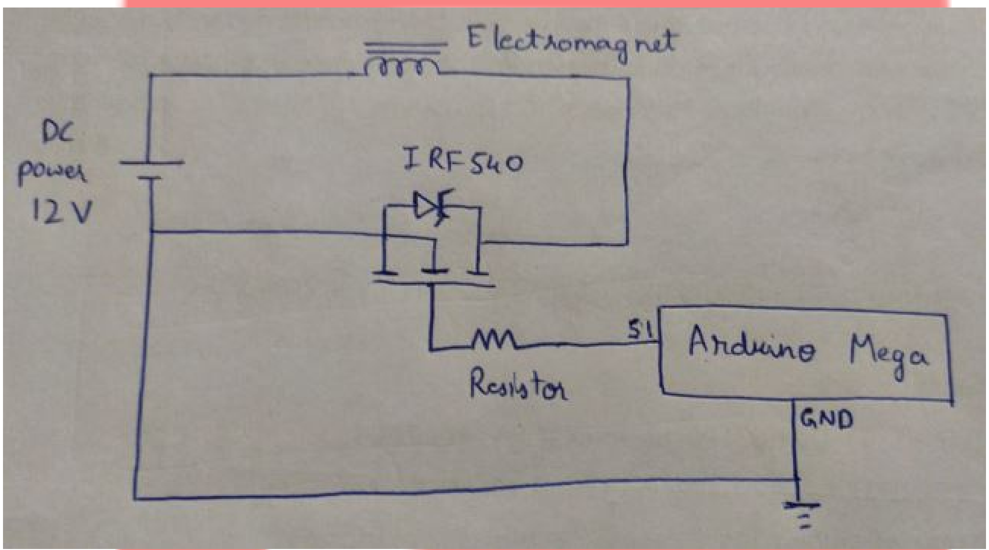

Figure 5: Connecting electromagnet to Arduino Mega