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MEM 455 – Introduction to Robotics

Final Design Report – Soil sample robot

Proposed Task

Scientist often uses robot to capture or sample the core soil in the deep ocean for research and experimentation. Soil sample provides valuable information to understand various natural phenomena and each layer of sediment of soil collected can be analyzed and dated using radiocarbon dating method. Thus for this design project, the focus will be on constructing a robot that can travel in the deep ocean to help scientist sampling the soil in the ocean.

This design project will be focusing on stakeholders in the research area especially for the marine scientist and oceanographer. The robot will also be used for educational purposes making the student and teacher as our additional stakeholders. To execute this project, several modifications need to be made on the current MeArm robot to achieve the desired task.

Needs

The main objective of this robot is to be able to sample the core soil in the deep ocean. The robot has to be able to work underwater flawlessly and move in the ocean in x-y direction. The robot should be able to sample soil in difficult terrain as well as in tight places in the ocean. Since the robot is intended to be used in the ocean, it needs to be durable enough to carry out it task. The robot also needs to be able to drill into different kind of soil successfully.

As for the needs for the student, the knowledge obtained from the MEM 455 class needs to be incorporated into the robot during the design and evaluation processes. Thus, the end product of the robot can be used for other educational purposes such as hands-on demonstration, in which the instructor and student can both interact with the robot. The cost for manufacturing the robot also needs to be at a reasonable price.

Below is the comprehensive list of the needs for the robot based on its priority (bold are the critical needs for the robot to success):

<u>Users' needs (Marine Scientist & Oceanographer):</u>

1. **The robot must be able to drill and sample the core soil**
2. **The robot needs to work underwater**
3. **The robot can move in the ocean**
4. **The robot able to reach difficult or tight places in the ocean**
5. Robot must be durable

<u>Student's need:</u>

1. **Utilize knowledge from MEM 455 into the robot**
2. Build the robot within time limit

<u>Teacher's need:</u>

1. Robot can be used for hands-on demonstration

Manufacturing need:

1. **The cost to build the robot must be affordable**

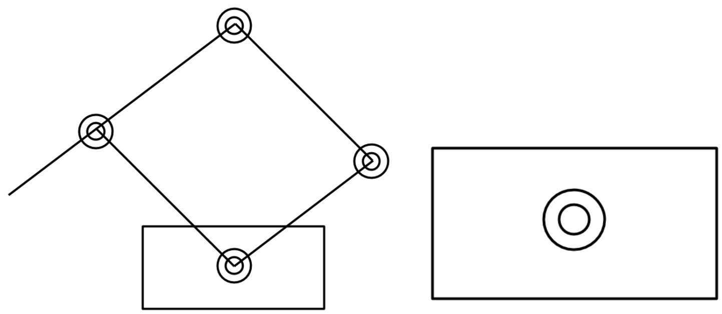
Specifications

The lists of needs are combined and converted to measurable specifications as follow (highlighted are the critical specifications for the robot to success):

No.	Need No.	Priority	Metric	Description	Target Value	Unit
1	Users' need 1	Primary	Volume	Measure volume of soil that can be sampled per session	0<x<20 cm^3	cm^3
			Newton	Measure of force that the drill bit need to apply	>0.4 N	N
			Error	Measure of accuracy of the drill bit	0<x<3 mm deviation	mm
2	Users' need 2	Primary	Ingress Protection (IP) rating	Measure degree protection of the robot against solid and liquid objects	IP68	IP
3	Users' need 3	Primary	Workspace	Specification of the end-effector configuration	(x,y,z) & (θ,ϕ)	Coord inates
			Velocity	Measure the speed of the robot	>2cm/s	cm/s
4	Users' need 4	Primary	Degrees of freedom	Measure degree of freedom of the robot	≥4	DOF
5	Users' need 5	Tertiary	Shelf-life	Measure of how long the product can be used without servicing	>1	Year
6	Student's need 1	Primary	No. of class concepts applicable	Usage of class concepts: DOF, Workspace, Kinematics, Simulation, Rigid-Body Motions	>3 Concepts	-
7	Student's need 2	Primary	Deadline	Complete the robot by due date	March 14, 2018	-
8	Teacher's need 1	Secondary	STEM Relation	Number of STEM classes the product applies to: MEM 455, MEM 435, MEM	2	Classe s

				491		
9	Manufacturing need 1	Secondary	Cost to make	Measure of cost to make the product	≤$100	USD

MeArm Models



MeArm linkages and top view with joints.

Using the Grubler's Formula, the number of degrees of freedom of the robot can be calculated as follows:

$$dof = m(N - 1 - J) + \sum_{i=1}^{J} f_i$$

$$No\ of\ link, N = 5$$

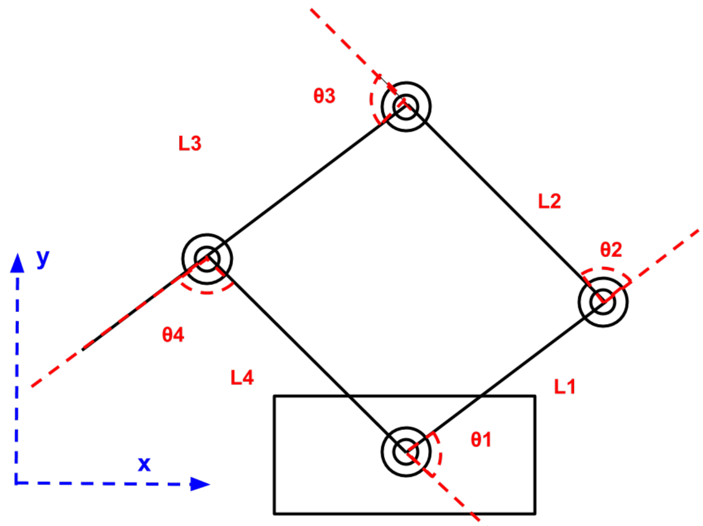
$$m = 3$$

$$No\ of\ joints, J = 4\ Revolute\ Joints$$

$$MeArm\ DOF = 3(5 - 1 - 4) + 4 = 4$$

The end-effector configuration of the MeArm can be described by using 4 parameters (x,y,z,ϕ), where the (x,y,z) denotes the Cartesian position of the end-effector and ϕ denotes the orientation of end-effector from the rotation at the base. The workspace of the MeArm can be defined as the reachable points in (x,y,z) Cartesian plane.

MeArm Jacobian Matrix



The forward kinematics of the the MeArm are as follow:

$$x1 = L1\cos(\theta1) + L2\cos(\theta1+\theta2) + L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4)$$

$$x2 = L1\sin(\theta1) + L2\sin(\theta1+\theta2) + L3\sin(\theta1+\theta2+\theta3) + L4\sin(\theta1+\theta2+\theta3+\theta4)$$

Differentiate both of the sides with respect to time yields:

$$\dot{x1} = -L1\sin(\theta1)\,\dot{\theta1} - L2\sin(\theta1+\theta2)\left(\dot{\theta1}+\dot{\theta2}\right) - L3\sin(\theta1+\theta2+\theta3)\left(\dot{\theta1}+\dot{\theta2}+\dot{\theta3}\right) - L4\sin(\theta1+\theta2+\theta3+\theta4)\left(\dot{\theta1}+\dot{\theta2}+\dot{\theta3}+\dot{\theta4}\right)$$

$$\dot{x2} = L1\cos(\theta1)\,\dot{\theta1} + L2\cos(\theta1+\theta2)\left(\dot{\theta1}+\dot{\theta2}\right) + L3\cos(\theta1+\theta2+\theta3)\left(\dot{\theta1}+\dot{\theta2}+\dot{\theta3}\right) + L4\cos(\theta1+\theta2+\theta3+\theta4)\left(\dot{\theta1}+\dot{\theta2}+\dot{\theta3}+\dot{\theta4}\right)$$

The result then can be arrange in the form of $\dot{x} = J(\theta)\dot{\theta}$:

$$\begin{bmatrix} \dot{x}1 \\ \dot{x}2 \end{bmatrix} = \begin{bmatrix} -L1\sin(\theta1) - L2\sin(\theta1+\theta2) - L3\sin(\theta1+\theta2+\theta3) - L4\sin(\theta1+\theta2+\theta3+\theta4) & -L2\sin(\theta1+\theta2) - L3\sin(\theta1+\theta2+\theta3) - L4\sin(\theta1+\theta2+\theta3+\theta4) & -L3\sin(\theta1+\theta2+\theta3) - L4\sin(\theta1+\theta2+\theta3+\theta4) & -L4\sin(\theta1+\theta2+\theta3+\theta4) \\ L1\cos(\theta1) + L2\cos(\theta1+\theta2) + L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) & L2\cos(\theta1+\theta2) + L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) & L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) & L4\cos(\theta1+\theta2+\theta3+\theta4) \end{bmatrix} \begin{bmatrix} \dot{\theta}1 \\ \dot{\theta}2 \\ \dot{\theta}3 \\ \dot{\theta}4 \end{bmatrix}$$

The end effector linear velocity $\dot{x}$ can be written as $v_{tip} = J_v(\theta)\dot{\theta}$, where $J_v(\theta)$ is the corresponding column of $\dot{x}$. The last row of each $J(\theta)$ is equal to zero as there's no linear velocity in z-direction according to the frame initial setup.

$$J_{v1}(\theta) = \begin{matrix} -L1\sin(\theta1) - L2\sin(\theta1+\theta2) - L3\sin(\theta1+\theta2+\theta3) - L4\sin(\theta1+\theta2+\theta3+\theta4) \\ L1\cos(\theta1) + L2\cos(\theta1+\theta2) + L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) \\ 0 \end{matrix}$$

$$J_{v2}(\theta) = \begin{matrix} -L2\sin(\theta1+\theta2) - L3\sin(\theta1+\theta2+\theta3) - L4\sin(\theta1+\theta2+\theta3+\theta4) \\ L2\cos(\theta1+\theta2) + L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) \\ 0 \end{matrix}$$

$$J_{v3}(\theta) = \begin{matrix} -L3\sin(\theta1+\theta2+\theta3) - L4\sin(\theta1+\theta2+\theta3+\theta4) \\ L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) \\ 0 \end{matrix}$$

$$J_{v4}(\theta) = \begin{matrix} -L4\sin(\theta1+\theta2+\theta3+\theta4) \\ L4\cos(\theta1+\theta2+\theta3+\theta4) \\ 0 \end{matrix}$$

The Jacobian for angular velocity can be easily found by observing the MeArm.

$$J_\omega(\theta) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Full representation of Jacobian for the end-effector is then:

$$J_s(\theta) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ J_{v1}(\theta) & J_{v2}(\theta) & J_{v3}(\theta) & J_{v4}(\theta) \end{bmatrix}$$

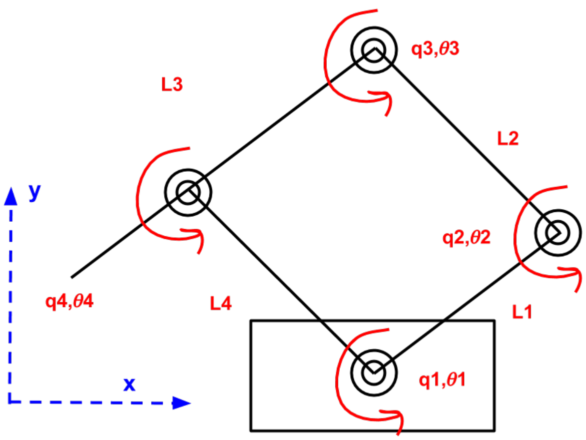
The twist of the end-effector can be represented based on the relationship, $V_s = J_s(\theta)\dot{\theta}$.

$$V_s = \begin{bmatrix} \omega_s \\ v_s \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ J_{v1}(\theta) & J_{v2}(\theta) & J_{v3}(\theta) & J_{v4}(\theta) \end{bmatrix} \dot{\theta}$$

The required wrench for the robot to stay in equilibrium is related by the following equation, $\tau = J^T(\theta)F$, where τ is joint torques needed for the robot to respond to external wrench F.

$$\tau = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ J_{v1}(\theta) & J_{v2}(\theta) & J_{v3}(\theta) & J_{v4}(\theta) \end{bmatrix}^T F$$

$\tau\dot{\theta} = V_s^T Fr$ is used to relate the twist, Vs, and the required wrench on the end effector, Fr.



To develop the mathematical description of the MeArm by inspection, the origin was chosen as q1. C1 represents cos (θ_1), while C12 represents cos $(\theta_1 + \theta_2)$ and so on.

$$\omega_{s1} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, q1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, v_{s1} = -\omega_{s1} \times q1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\omega_{s2} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, q2 = q1 + \begin{bmatrix} L1c1 \\ L1s1 \\ 0 \end{bmatrix}, v_{s2} = -\omega_{s2} \times q2 = \begin{bmatrix} L1s1 \\ -L1c1 \\ 0 \end{bmatrix}$$

$$\omega_{s3} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, q3 = q2 + \begin{bmatrix} L2c12 \\ L2s12 \\ 0 \end{bmatrix}, v_{s3} = -\omega_{s3} \times q3 = \begin{bmatrix} L1s1 + L2s12 \\ -L1c1 - L2c12 \\ 0 \end{bmatrix}$$

$$\omega_{s4} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, q4 = q3 + \begin{bmatrix} L3c123 \\ L3s123 \\ 0 \end{bmatrix}, v_{s4} = -\omega_{s4} \times q4 = \begin{bmatrix} L1s1 + L2s12 + L3s123 \\ -L1c1 - L2c12 - L3c123 \\ 0 \end{bmatrix}$$

$$J_s(\theta) = \begin{bmatrix} \omega_{s1} & \omega_{s2} & \omega_{s3} & \omega_{s4} \\ v_{s1} & v_{s2} & v_{s3} & v_{s4} \end{bmatrix}$$

The Jacobian matrix formed based on the example 5.2 from textbook is different with the previously made Jacobian matrix using forward kinematic analysis. This is most likely caused by simplification made on the linkage of MeArm during the analysis of the MeArm by inspection. The Jacobian matrix is also obtained using MATLAB for the linear velocity, and the result agrees with the Jacobian from forward kinematic analysis.

```
>> pretty(J_v)
[[- #2 - L2 sin(theta1 + theta2) - L1 sin(theta1) - #3,

  - #2 - L2 sin(theta1 + theta2) - #3, - #2 - #3, -#2],

  [#1 + L2 cos(theta1 + theta2) + L1 cos(theta1) + #4,

  #1 + L2 cos(theta1 + theta2) + #4, #1 + #4, #1],

  [0, 0, 0, 0]]

where

   #1 == L4 cos(theta1 + theta2 + theta3 + theta4)

   #2 == L4 sin(theta1 + theta2 + theta3 + theta4)

   #3 == L3 sin(theta1 + theta2 + theta3)

   #4 == L3 cos(theta1 + theta2 + theta3)
```

To setup the MeArm for inverse kinematic analysis, the position of end-effector can be described from the forward kinematic analysis.

$$x1 = L1\cos(\theta 1) + L2\cos(\theta 1 + \theta 2) + L3\cos(\theta 1 + \theta 2 + \theta 3) + L4\cos(\theta 1 + \theta 2 + \theta 3 + \theta 4)$$
$$x2 = L1\sin(\theta 1) + L2\sin(\theta 1 + \theta 2) + L3\sin(\theta 1 + \theta 2 + \theta 3) + L4\sin(\theta 1 + \theta 2 + \theta 3 + \theta 4)$$

A few constraints can be made from the design of the MeArm itself.

$$L2 = L4$$
$$L1 < L3$$
$$\theta_1 + \theta_2 + \theta_3 + \theta_4 = 360°$$

$$\theta_1 + \theta_4 = 180°$$
$$\theta_2 + \theta_3 = 180°$$

MeArm Evaluation

MeArm Specifications:
$L1 = 35mm$
$L2 = 80mm$
$L3 = 115mm$
$L4 = 80mm$
SG92R Micro Servomotor Torque (at 4.8V)=1.6kg-cm=0.156Nm

Desired critical specifications of the MeArm are as follow:

No.	Need No.	Priority	Metric	Description	Target Value	MeArm Evaluation
1	Users' need 1	Primary	Volume	Measure volume of soil that can be sampled per session	0<x<20 cm^3	Failed
			Newton	Measure of force that the drill bit need to apply	>2 N	
			Error	Measure of accuracy of the drill bit	0<x<3 mm deviation	
2	Users' need 2	Primary	Ingress Protection (IP) rating	Measure degree protection of the robot against solid and liquid objects	IP68	Failed
3	Users' need 3	Primary	Workspace	Specification of the end-effector configuration	(x,y,z) & (θ,ϕ)	Failed
			Velocity	Measure the speed of the robot	>2cm/s	
4	Users' need 4	Primary	Degrees of freedom	Measure degree of freedom of the robot	≥4 DOF	Pass
6	Student's need 1	Primary	No. of class concepts applicable	Usage of class concepts: DOF, Workspace, Kinematics, Simulation, Rigid-Body Motions	>3 Concepts	Pass
9	Manufacturing need 1	Secondary	Cost to make	Measure of cost to make the product	≤$100	Pass

To evaluate the performance of the MeArm, all the variables in the Jacobian matrix from forward kinematic analysis were evaluated with initial condition angles:

$$\theta_1 = 45°$$
$$\theta_2 = 90°$$
$$\theta_3 = 90°$$
$$\theta_4 = 135°$$

The resulting Jacobian matrix is:

```
J =

         0         0         0         0
         0         0         0         0
    1.0000    1.0000    1.0000    1.0000
         0    0.0247    0.0813         0
   -0.0331   -0.0579   -0.0013    0.0800
         0         0         0         0
```

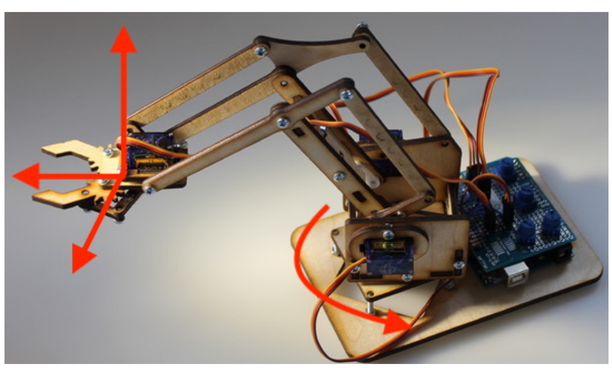
Thus, the torque needed for the MeArm to exert force of 2N can be calculated using $\tau = J^T(\theta)F$.

```
>> Torque=J_v'*[0;-2;0]

Torque =

    0.0663
    0.1158
    0.0026
   -0.1600
```

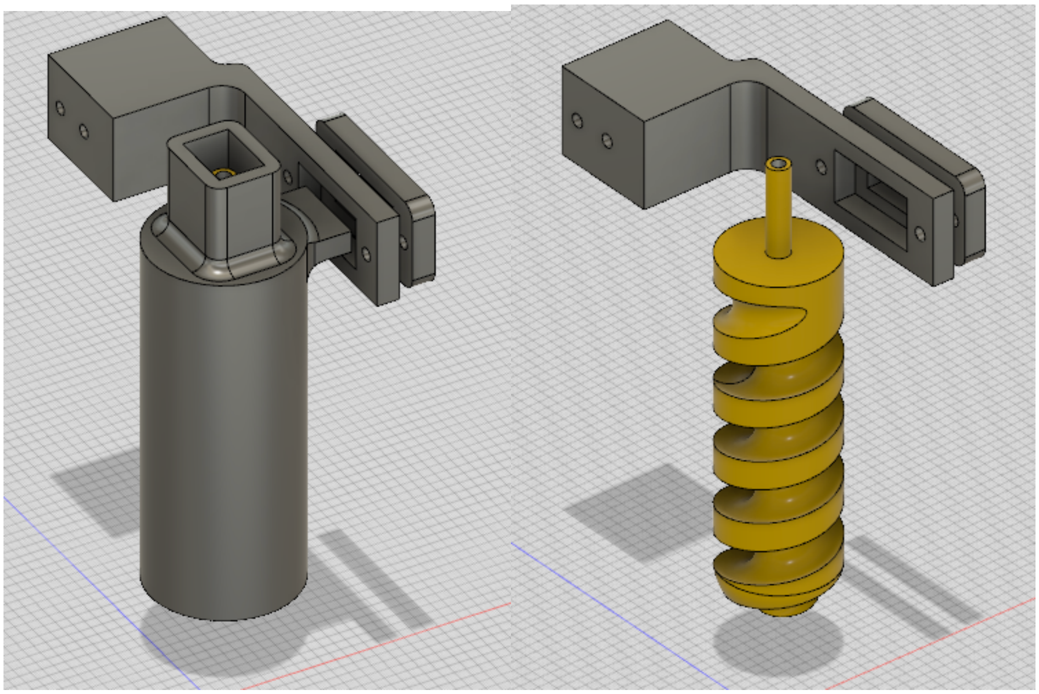
The torque experienced by the joint 4 (0.16 Nm) exceeds the torque that the servomotor could deliver. Thus, MeArm failed to meet specification #1. The next evaluation would be on the end-effector of the MeArm. The current design of the MeArm end-effector only able to move in (x,y,z,θ) as shown in the picture below. The restriction of the MeArm end-effector causes the MeArm failed to meet specification #3.



The MeArm design has successfully meet the specification #4 and #6 without needing any redesign. The current MeArm design has 4 DOF and can be used as a demonstration in several STEM classes in Drexel University.

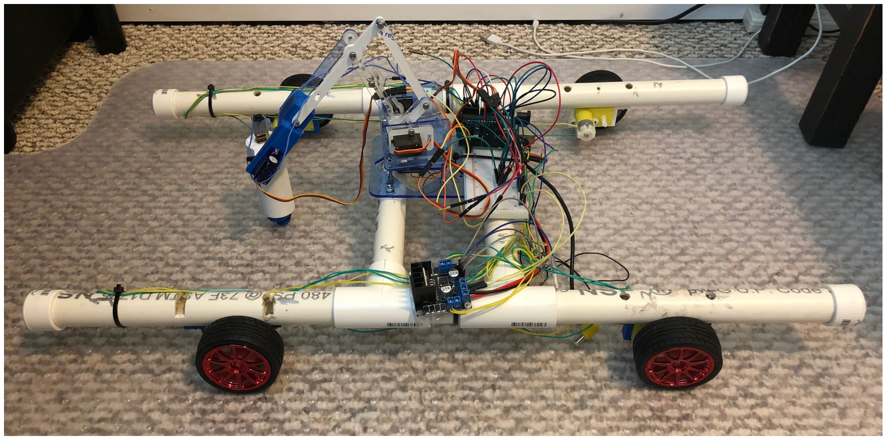
Concept for Redesign

The proposed redesign was developed after receiving feedback during the 1st oral presentation. The idea for redesigning the MeArm was inspired by the driller used to sample the core ice in Antarctica.



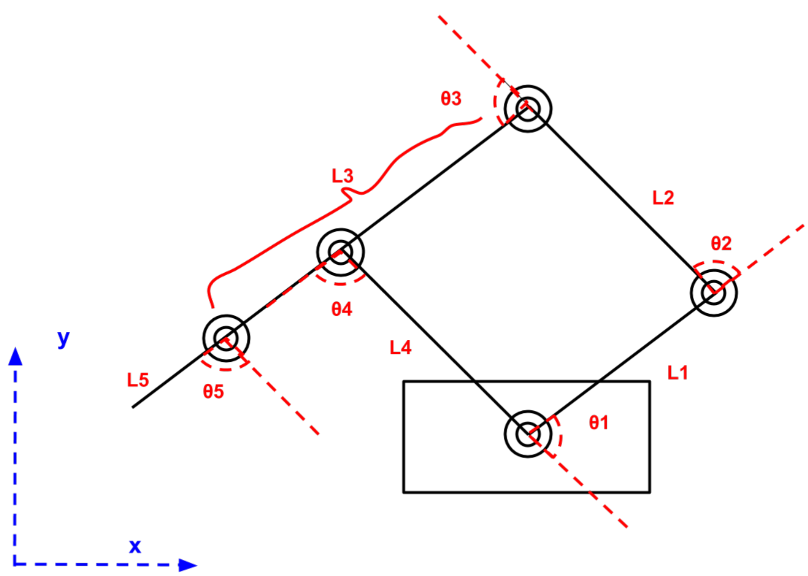
The MeArm requires a new design of the end-effector so it can effectively carry out the proposed task. Above is a picture of the final design made for the end-effector of the MeArm after several design iteration processes. This will replace the current claw end-effector of the MeArm. The advantages of this end-effector design are the additional degree of freedom, and also the increase in accuracy for the end-effector when drilling. The redesign of end-effector requires additional servomotor and a DC motor to drive the drill bit. The additional servomotor serves the purpose of rotating the drill bit at desired angle and also to provide additional torque for the end-effector. Inside of the cylinder body is a helical drill bit that was design to maximize the amount of soil that can be sampled at a time.

The next redesign of the MeArm will focus on the mobility of the MeArm. The current state of MeArm is that it is fixed at its base and it can't move, so the workspace of the MeArm is very limited. To achieve the critical specifications and needs, a new frame for the base was designed.



The new frame design has wide area with low center of gravity to increase the MeArm stability when operating. The dimension of the base is 70 $cm \times 30\ cm$, and the clearance from the ground is 5.5 cm. It was equipped with 4 6V DC motors that were controlled using Arduino Uno with a L298N motor driver. The addition of wheels to the base of the MeArm has greatly increases the workspace area of the MeArm. All the electronic was powered by a 12V DC battery and converted to 5V input for the servomotors using the built in step down in the L298N motor driver.

Engineering Analysis



The forward kinematics of the soil sample robot are as follow:

$$x1 = L1\cos(\theta1) + L2\cos(\theta1+\theta2) + L3\cos(\theta1+\theta2+\theta3) + L4\cos(\theta1+\theta2+\theta3+\theta4) + L5\cos(\theta1+\theta2+\theta3+\theta4+\theta5)$$

$$x2 = L1\sin(\theta1) + L2\sin(\theta1+\theta2) + L3\sin(\theta1+\theta2+\theta3) + L4\sin(\theta1+\theta2+\theta3+\theta4) + +L5\sin(\theta1+\theta2+\theta3+\theta4+\theta5)$$

The procedures for calculating Jacobian from forward kinematics analysis were repeated again for the new redesign. Both sides of the equations were differentiated with respect to time and rearranged in the form of $\dot{x} = J(\theta)\dot{\theta}$. Below is the Jacobian with respect to linear velocity.

$$J_v(\theta) = \begin{bmatrix} -\#4-\#7-L1\sin(\theta1)-\#1-\#5 & -\#4-\#7-\#1-\#5 & -\#4-\#1-\#5 & -\#4-\#1 & -\#1 \\ \#3+\#8+L1\cos(\theta1)+\#2+\#6 & \#3+\#8+\#2+\#6 & \#3+\#2+\#6 & \#3+\#2 & \#2 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

```
where

   #1 == L5 sin(theta1 + theta2 + theta3 + theta4

      + theta5)

   #2 == L5 cos(theta1 + theta2 + theta3 + theta4

      + theta5)

   #3 == L4 cos(theta1 + theta2 + theta3 + theta4)

   #4 == L4 sin(theta1 + theta2 + theta3 + theta4)

   #5 == L3 sin(theta1 + theta2 + theta3)

   #6 == L3 cos(theta1 + theta2 + theta3)

   #7 == L2 sin(theta1 + theta2)

   #8 == L2 cos(theta1 + theta2)
```

MeArm Specifications:
$L1 = 35mm$
$L2 = 80mm$
$L3 = 115mm$
$L4 = 80mm$
$L5 = 100mm$

Initial condition angles:
$\theta_1 = 45°$
$\theta_2 = 90°$
$\theta_3 = 90°$
$\theta_4 = 135°$
$\theta_5 = 0°$

The new redesign of the end-effector increased the degree of freedom of the MeArm robot, where the pitch of the drill bit can be rotated between 0° to 180° from the reference line. For the initial condition, the pitch was set to zero and the length of the drill bit is equal to 10cm. One servomotor with torque stall equals to 0.156 Nm was attached to the joint 5 to control the pitch and providing extra torque to the end-effector.

The Jacobian matrix was calculated after all the variable was defined. Below is the result for the Jacobian matrix.

```
J =

         0         0         0         0         0
         0         0         0         0         0
    1.0000    1.0000    1.0000    1.0000    1.0000
         0    0.0247    0.0813         0         0
    0.0669    0.0421    0.0987    0.1800    0.1000
         0         0         0         0         0
```

Calculating the torque needed for the end-effector to exert 2N in y-direction yields:

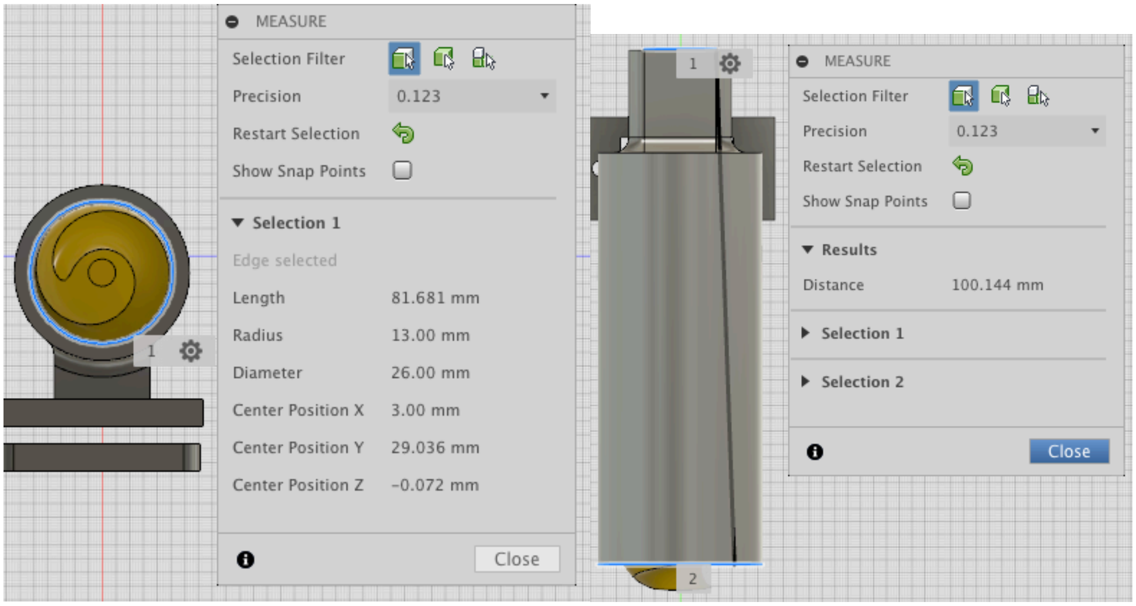
```
>> Torque=J_v'*[0;-2;0]

Torque =

   -0.1337
   -0.0842
   -0.1974
   -0.3600
   -0.2000
```

The amount of torque needed for the joint 5 is lower than the maximum available torque from the 2 servomotors used in the redesign MeArm. Thus, the available torque is equal to 0.112Nm. Thus, the redesign MeArm has successfully achieved specification #1.

$$(2\times 0.156Nm) - 0.2Nm = 0.112Nm$$



The amount of soil that the driller sample per session can be calculated easily using volume of cylinder body:

$$\pi * \left(\frac{13mm}{10}\right)^2 * \left(\frac{100mm}{10}\right) = 53cm^3$$

The speed of the robot movement in horizontal surface can be controlled using PWM in Arduino. Several tests were conducted to estimate the correct PWM so that the velocity of the robot must be at least 2cm/s. PWM signal value was set to 220 in the Arduino code to meet this specification.

The results of the MeArm redesign analysis were tabulated in the following table:

No.	Need No.	Priority	Description	Target Value	MeArm Evaluation	Current Value
1	Users' need 1	Primary	Measure volume of soil that can be sampled per session	0<x<20 cm^3	Pass	53 cm3
			Measure of force that the drill bit need to apply	>2 N		Available torque = 0.112 Nm
			Measure of accuracy of the drill bit	0<x<3 mm deviation	Failed	-
2	Users' need 2	Primary	Measure degree protection of the robot against solid and liquid objects	IP68	Failed	-
3	Users' need 3	Primary	Specification of the end-effector configuration	(x,y,z) & (θ,ϕ)	Pass	(x,y,z) & (θ,ϕ)
			Measure the speed of	>2cm/		3cm/s

			the robot	s		
4	Users' need 4	Primary	Measure degree of freedom of the robot	≥4 DOF	Pass	5 DOF
6	Student's need 1	Primary	Usage of class concepts: DOF, Workspace, Kinematics, Simulation, Rigid-Body Motions	>3 Concep ts	Pass	DOF, Workspace, Forward Kinematics, Manipulator Jacobians
9	Manufactu ring need 1	Secondary	Measure of cost to make the product	≤$100	Pass	$65

Based on the critical specifications and needs, most of the redesign aspect of the MeArm managed to overcome the problems and restrictions from the original design of the MeArm. However, the redesign failed to meet the drill bit accuracy for the specification #1 and the final robot build wasn't completely waterproof to meet specification #3. Power issues caused the servomotors to not working as smoothly as expected especially when multiple servomotors were running concurrently. This leads to the drill bit's accuracy issue when controlling the MeArm.

Appendices