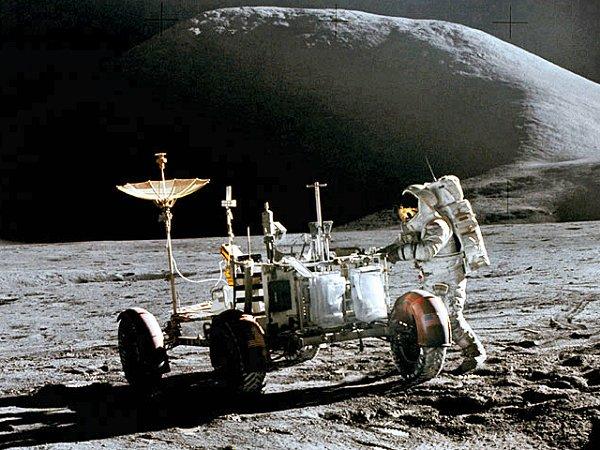
**Instrument Deployment Arm on Lunar Rover**

**2009**

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**MAE 345 Midterm Project**



**Abstract**

In this paper we present a proposal for the design of the instrument deployment arm for a lunar rover. The purpose of the rover is to examine geological structure on the Moon, specifically, to taking pictures of cross sections of rocks on the Moon. Such information is believed to yield useful insight on minerals available on the Moon, as well as prior existence of water and microorganisms.

The arm is to be placed folded up underneath the rover. After the rover is parked near a rock, the goal is for the arm extend out to engage to rock, drill into it, take pictures of the cross section exposed, and retrieve itself back to its folded position.

It is assumed that the rover is similar to the Mars Exploration Rover. The components of the arm are designed on computer using Pro Engineer, and the action of the arm is simulated in Matlab. Simulation includes the movement of the rocker bogie system, a well known device on the Mars Rover.

After detailed design and analysis of simulation, we have formed a very realistic and reasonably optimized design for the arm that can be easily manufactured and assembled as described, should the need arise.

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1. **Introduction**
   1. Background and motivation
   2. High Level Logic Flow inside Robot



* 1. Organization of paper

1. **Arm Configurations**
   1. **Overview of Components**

Before we talk about the arm components, we will first make a few assumptions on the dimensions of the rover: rover is about 1.2m wide, and around 1.5 m long; the chassis is lifted off ground for about 10 – 12 cm. The wheel width is about 15 cm, but wheels extend outside the chassis. These estimates are based on the Spirit and Opportunity Mar Exploration Rovers.

The Arm will be anchored beneath the vehicle, 5 cm to the **right** of the **left** forward wheel, 5 cm from forward edge of rover, and 2 cm below the rover’s chassis. This position is referred to as the base of the arm. This means we have at least a meter laterally and 10 cm vertically to work with (as space for the arm).

[Diagram]

The orientation we will be using is :

Forward = positive x.

Upward = positive y.

Right = positive z.

Origin = base of arm.

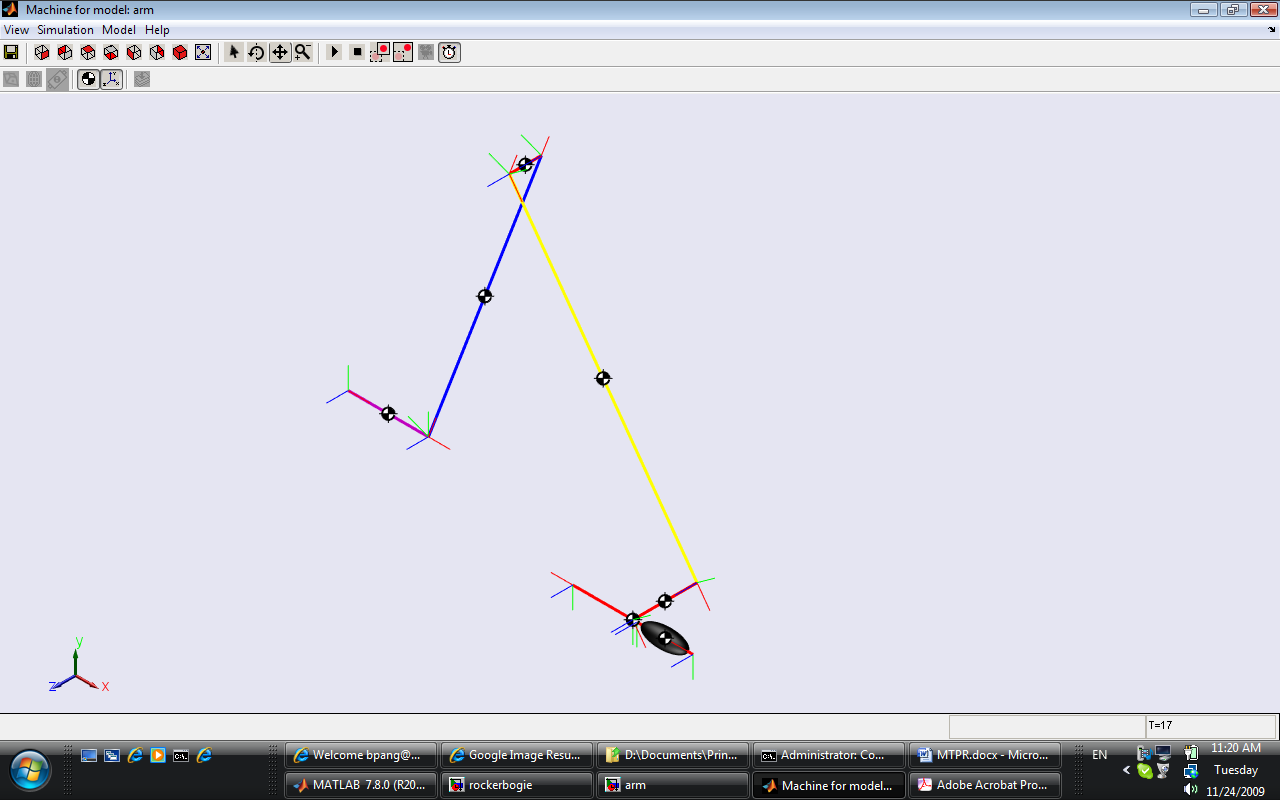
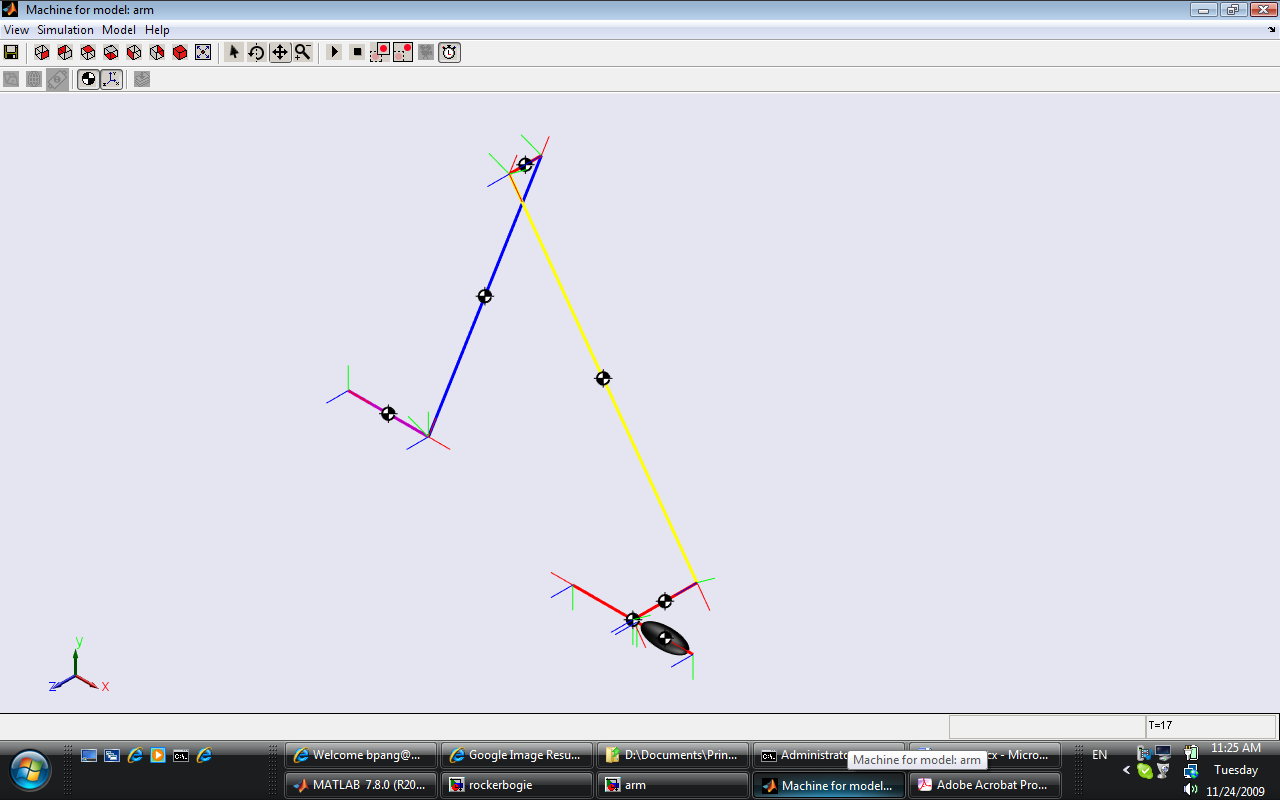
(This is a left handed system, but Matlab uses it, so we have adopted it here.)

The arm will consists of 4 links, as described below from proximal to distal.

The **neck piece** is a short piece pointing forward in the x direction, and based at the arm base. It yaws laterally, around the y axis, and it’s purpose it to allow folding and unfolding, as well as to provide lateral flexibility of the arm’s position.

The neck piece is then connected to the **upper arm**, a long link that pitches around the z axis. It is in turn connected to the **lower arm**, via a small **connecter piece**. The upper arm and lower arm are parallel, but the connector between them is perpendicular to both of them. It’s purpose is to place some lateral distance (in the z direction) so that lower arm may fold completely on upper arm, and also to make room for actuators.

The lower arm is connected to the **manipulator** (or tool box), again via a connector piece. The manipulator piece is parallel to lower arm, and spins (up to 360 degrees) in the vertical plane. It is a stick shaped body, with its middle attached to the connecter, which is attached to the lower arm. The 2 ends of the manipulator are the drill head, and the microscopic imager, respectively.



Base of arm

camera

Drill head (thrusting and spinning)

connector

manipulator

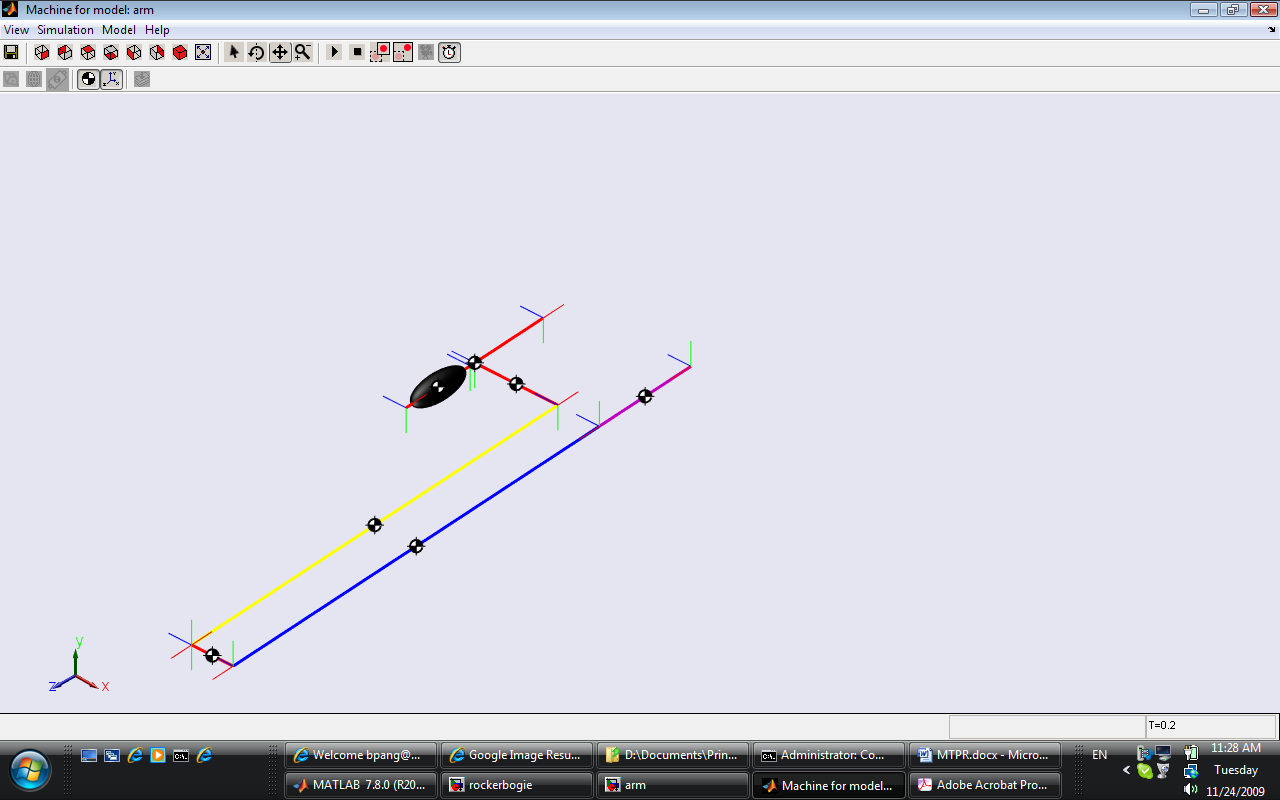
connector

Lower arm

Upper arm

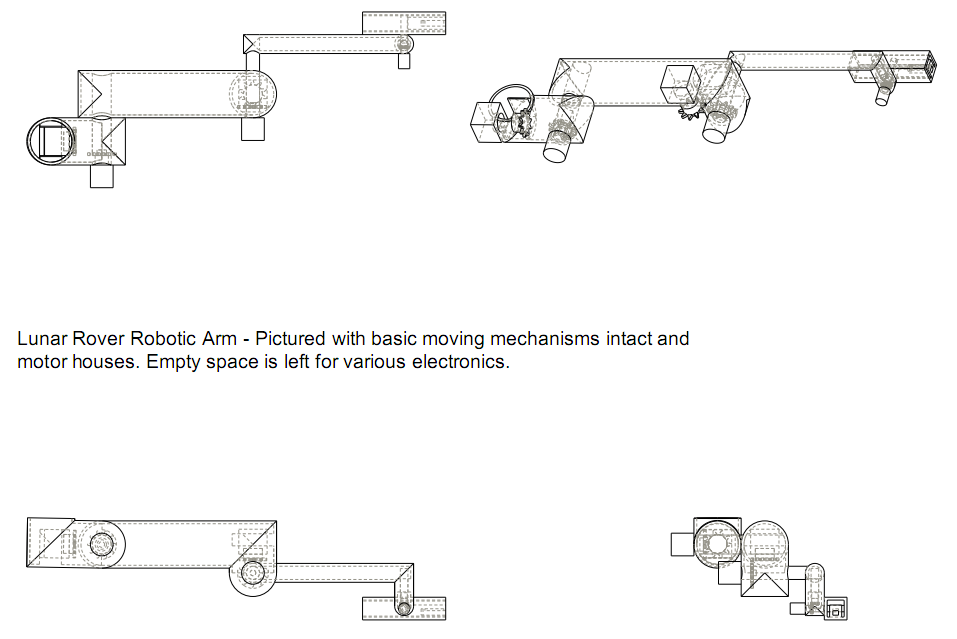
Neck piece

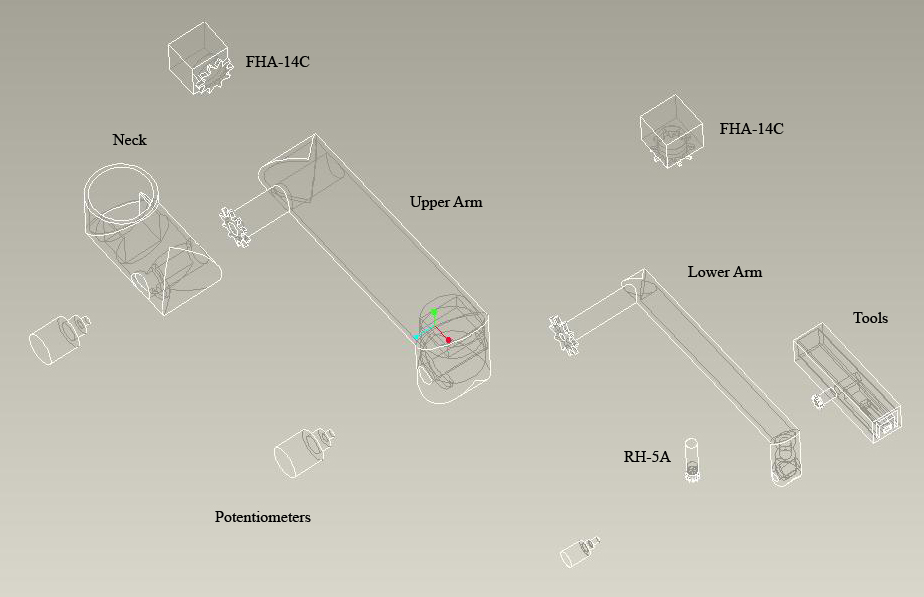
With such design, the arm has ample freedom in x, y, and z directions, and is able to completely fold on its self into a very compact form. For detailed consideration in range of motion, see section 2.3. For detailed sizes of parts, see section 2.2.



We refer to this position shown in the above diagram as the curled up position. It will be the starting point and end point of motion.

* 1. **Designs of Individual Mechanical Parts (Justin)**







Simple potentiometer

Wikipedia entry

these are the volumes for the three main parts from pro e. the lengths you can get from the engineering drawings i just sent you, and yes i can see the changes on the google docs, i just can't uload till i go back to the room and use my desktop

Upper arm

VOLUME = 2.6182357e+06 MM^3

Lower arm

VOLUME = 7.4661957e+05 MM^3

Neck piece

VOLUME = 1.2343187e+06 MM^3

i realized i forgot about the endeffector part,

VOLUME =  4.5308578e+05  MM^3

also, for each part, add 1 to 1.5 kg for miscellaneous extra electronics.

the toolcase should be around 4.5 kg

the small motor is .09kg

the large ones are 1.2 kg each, so don't forget to add those weights where the motors are

* 1. **A model of the Arm used in Simulation**

The above mechanical parts are too complicated to be used in a simulation. Below, we make a few simplifying assumptions about the geometry, based on the specifications above. The resulting geometry will be used for modeling and simulation.

As the reader can check in the Materials section, the material we will use for the main body of the links has density 1.78 g/cm^3.

**Joint 1:** Base of arm to neck piece.

1 DOF, rotate (yaws) about y-axis

Curled up position: theta = 90.

Forward position: theta = 0.

Range of motion: 90 ~ -60 (limited by the presence of left forward wheel)

**The neck piece** will be modeled as a hollow cylinder, with length 20 cm (26 cm as in the mechanical drawing, minus 6 cm of the radius of joint), inner radius 5 cm, outer radius 6 cm. Thus it’s volume in model is

Adding 1.5 kg (for details, see Sensors and Actuators section) for motor placed in the neck piece, we have a total of 2.73 kg.

We calculate the moment of inertia of the hollow tube using this formula:

Where m is the mass for the tube only.

So we get

The motor is placed in the center of the piece, so does not affect I much. In the model, it only contributes to the mass.

At rest position, neck piece lies along the x axis. At curled up position, it lies along the z axis.

**Joint 2:** neck to upper arm

1 DOF, rotate about z axis

Curled up position: theta = 0 deg

Pointing straight forward: theta = 0 deg

Pitching upward: theta > 0.

Range: 0 – 75

**The upper arm** will be modeled as a hollow cylinder, with a “center of joint to center of joint” length of 40 cm (subtracting the 6 cm of radius of the 2 joints on either end), an outer radius of 6 cm and inner radius of 5 cm. Thus its volume is ,

Adding for some wiring, we have a mass of about 2.8 kg.

The motor to activate the lower arm is placed in the connector link to follow.

We calculate the moment of inertia using the same formula to get,

At rest position, upper arm lies along the x axis, straight with neck piece. At curled up position, it lies along the z axis, straight with neck piece.

**The connector piece** is welded on to the distal end of the upper arm, always perpendicular to it, lying to the positive z side in straight forward position. In the model, it has a length of 8 cm, and an outer radius of 5 cm, an inner radius of 4 cm. It also has a motor inside, weighing 1.5 kg. It’s own body weight is,

Thus total weight is 2.4 kg. Assuming weight is distributed evenly, we calculate the moment of inertia of this link as a solid cylinder:

**Joint 3**: upper arm to lower arm

1 DOF, rotate about z axis

Curled up position: theta = -180 deg

Straight forward: theta = 0 deg

Bent down: theta < 0

Range: 0 -180

**The lower arm** will be modeled as a hollow cylinder, with a “center of joint to center of joint” length of 40 cm, an outer radius of 2.5 cm and inner radius of 1.75 cm. Thus its volume is ,

Adding for some wiring, we have a mass of about 3.5 kg.

The motor to activate the manipulator/tool box is placed in the connector link to follow.

We calculate the moment of inertia using the same formula to get,

At rest position, lower arm lies along the x axis, straight with upper arm, perpendicular with connectors. At curled up position, it lies along the z axis, side by side with upper arm.

**The connector piece** is welded on to the distal end of the lower arm, always perpendicular to it, lying to the positive z side in straight forward position. In the model, it has a length of 8 cm, and an outer radius of 2.5 cm, an inner radius of 1.75 cm. It also has a small motor inside, weighing 0.1 kg. Its own body weight is,

Thus total weight is 0.25 kg. Assuming weight is distributed evenly, we calculate the moment of inertia of this link as a solid cylinder:

**Joint 4:** lower arm to manipulator

1 DOF, rotate about z axis

Curled up position: theta = 0.

Range: 360 deg rotation.

**Manipulator/Tool Box** will be modeled as a solid cylinder, with a length of 20 cm, an outer radius of 6 cm, and a mass of 4.5 kg, including Microscopic imager, drill, actuator, and wiring.

The motor to activate the manipulator/tool box is placed in the connector preceding it.

We calculate the moment of inertia for solid cylinder:

At rest position, lower arm lies along the x axis, straight with upper arm, perpendicular with connectors. At curled up position, it lies along the z axis, side by side with upper arm.

* 1. **Range of Action**

[diagram]

1. **Materials (Justin)**

Carbon fiber: Fiber-reinforced materials such as carbon, aramid and glass composites have the highest strength and stiffness-to-weight ratios among engineering materials. For demanding applications such as spacecraft, aerospace and high-speed machinery, such properties make for a very efficient and high-performance system. Carbon fiber composites, for example, are five times stiffer than steel for the same weight allowing for much lighter structures for the same level of performance. In addition, carbon and aramid composites have close to zero coefficients of thermal expansion, making them essential in the design of ultra-precise work stations.

1.78 g/cm^3.

1. **Sensors and Actuators (Justin)**
   1. Sensor Choice: Technical Specifications
   2. Sensor Choice: Advantages and Disadvantages
   3. Actuator Choice: Technical Specifications
   4. Actuator Choice: Advantages and Disadvantages

Detailed list of parameters and ranges

Sensors:

With the actuation and mechanics finalized, sensors need to be selected in order to provide feedback for the control system that shall be implemented. Two types of sensors are required in this design: angular position sensors as well as a linear position sensor for the RAT. Angular sensors can easily be implemented with high grade potentiometers, which can discern the angle via changing resistances. These can be mounted opposite the incoming gear shaft on a joint and fastened to the non-rotating link. They come in all shapes and sizes, and can be quite small. However, a small shell and small electronics to convert the signal will need to be placed there as well, but even so, these sensors would not add much weight or volume to the design. In the PRO Engineer model, these sensors, like the motors, are simplified and can be seen in the final design. As for the linear position sensor, a strain gauge can be utilized in order to tell if the RAT has moved a certain distance. Once the target distance is reached, a signal can be sent to the actuator to retract the RAT. This is also quite simple, and although it is not depicted in the model, space in the toolset was left for it.

It was mentioned before that all the main computing will be processed on the rover, and likewise, the position sensors mounted on the arm will feed information back to the central infrastructure. Perhaps, in order to reduce cable clutter, these signals could be combined with the actuator signals via electronics within the links and sent together for processing on the rover.

1. **Mechanism of Action**
   1. **Overview**

This section describes how the arm will move from curled up position to engage target.

The oeverall flow is: take the coordinate of the rock, calculate the required angles at the reference position, and find a path to transfer the arm to that reference position, where path is specified by functions of joint angles with respect to time. These angle trajectories are then fed to the control system, which will realize the required angles.

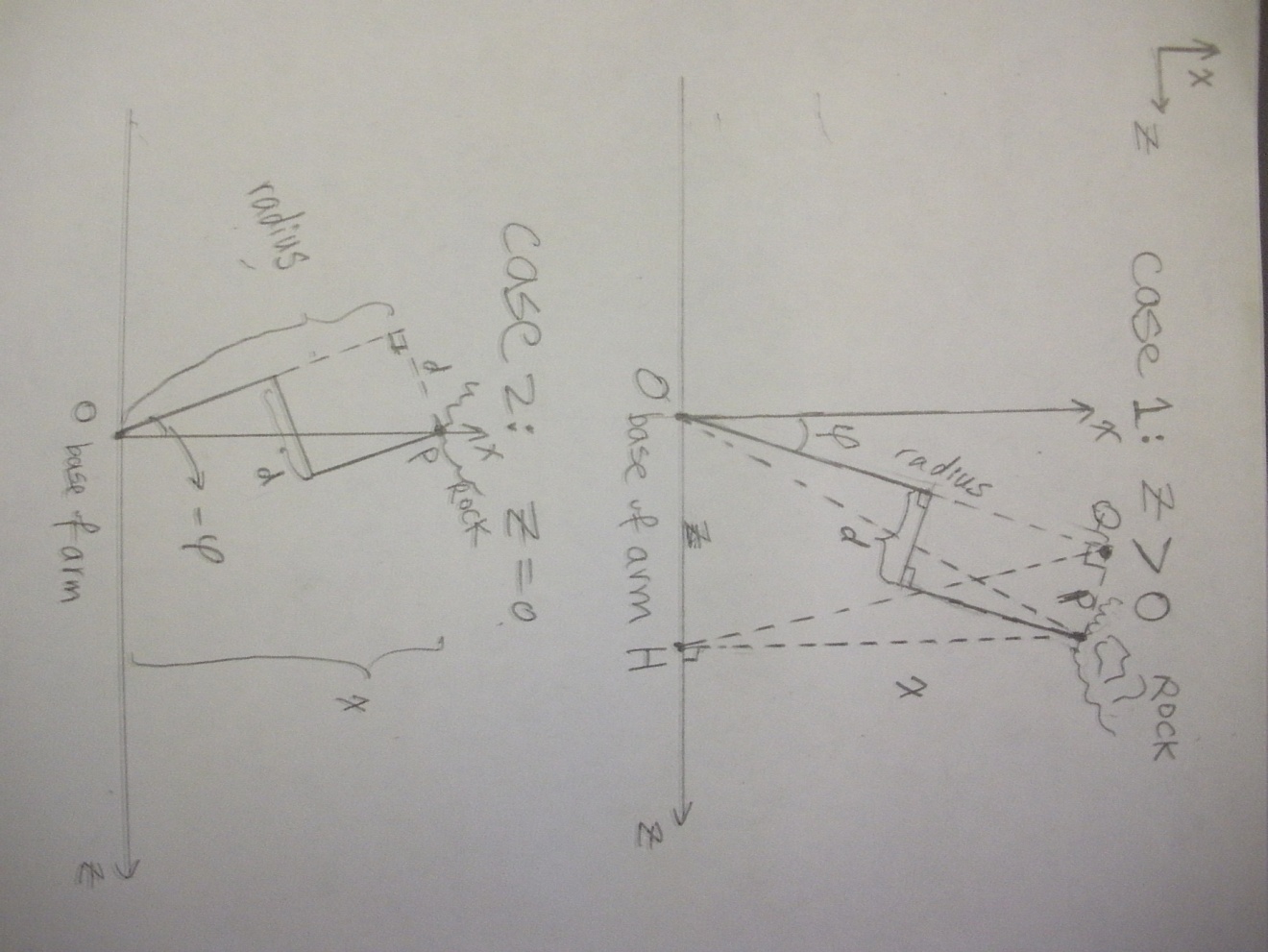
As a first approximation, we simplify the problem and assume that base of arm is ground, i.e. fixed. At the end of this section, we take up the effect of rocker-bogie bounces, and our solution to deal with it.

* 1. **Calculating the Reference Position**

A core part of action mechanism is to figure out what angles each joint needs to be at each moment in time in order to reach the reference position for a given rock surface positioned at

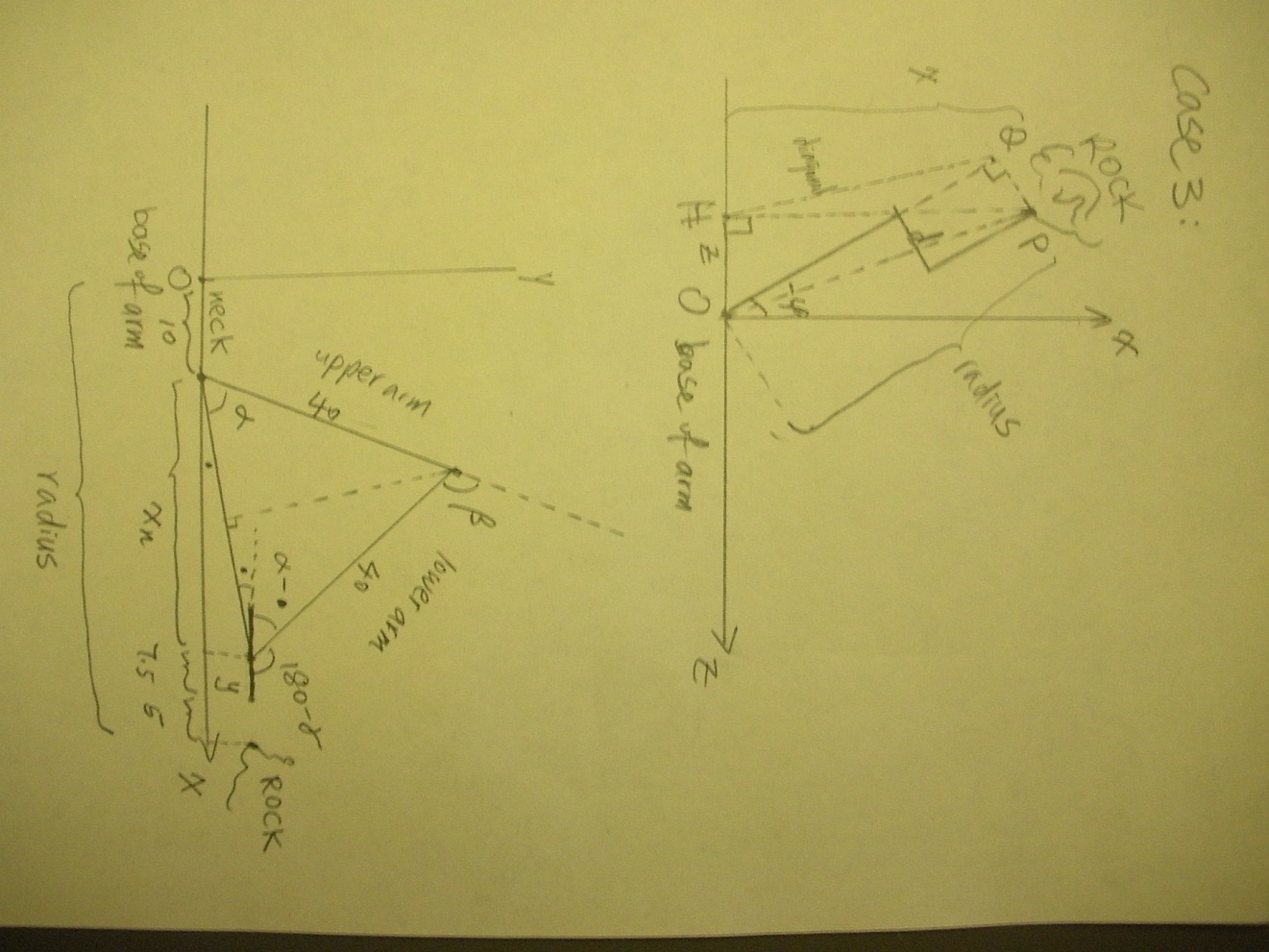
(x, y, z). The first step in this procedure is to figure out the FINAL angles we need each joint to have, when the arm is AT the reference position.

This part is non-trivial, and is analyzed below. For the matlab code implementing the ideas presented below, see Appendix A.

Step 1: Ignore y coordinate (vertical) for now. Using only the x and z coordinates of rock surface, we can already determine the neck yaw angle (φ) needed, as well as the “radius”, which is defined as the (axial) distance from base of arm to rock *as if there were no lateral displacement*. It is drawn in the diagrams below. Also, lateral displacement occurs in 2 parts, 1 on the connector between upper arm and lower arm, which has length 4, the other on the connector between lower arm and manipulator, which has length 8. So total lateral displacement = 12cm in this design. In the derivations to follow, we combine these 2 displacement into 1 equivalent lateral displacement, d.

Thus the current problem is: given x, z, d, find φ and radius.

We break the situation down into 3 cases because each case has a slightly different geometry: z >0 (case 1), z=0 (case 2), z<0 (case 3).

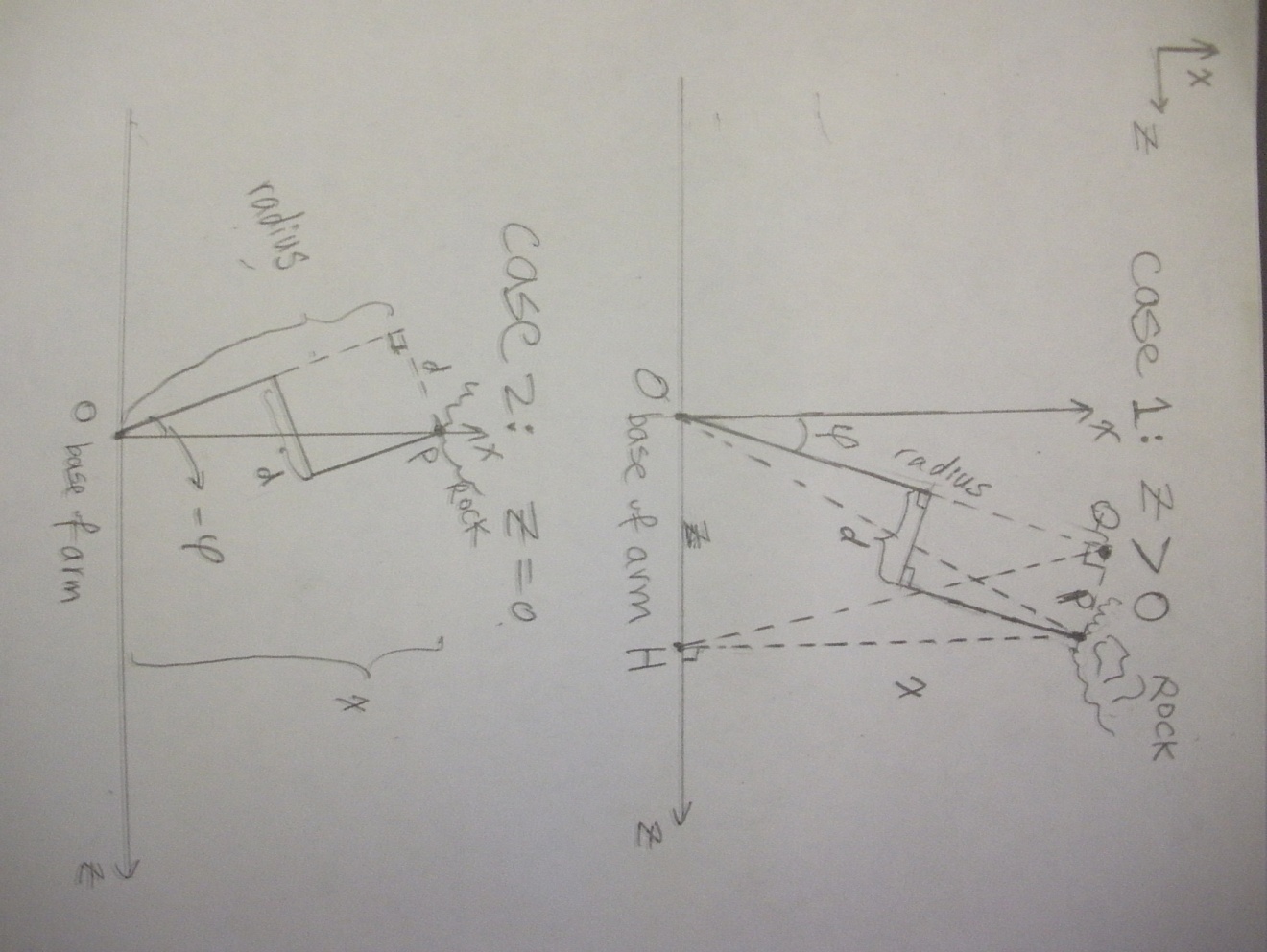


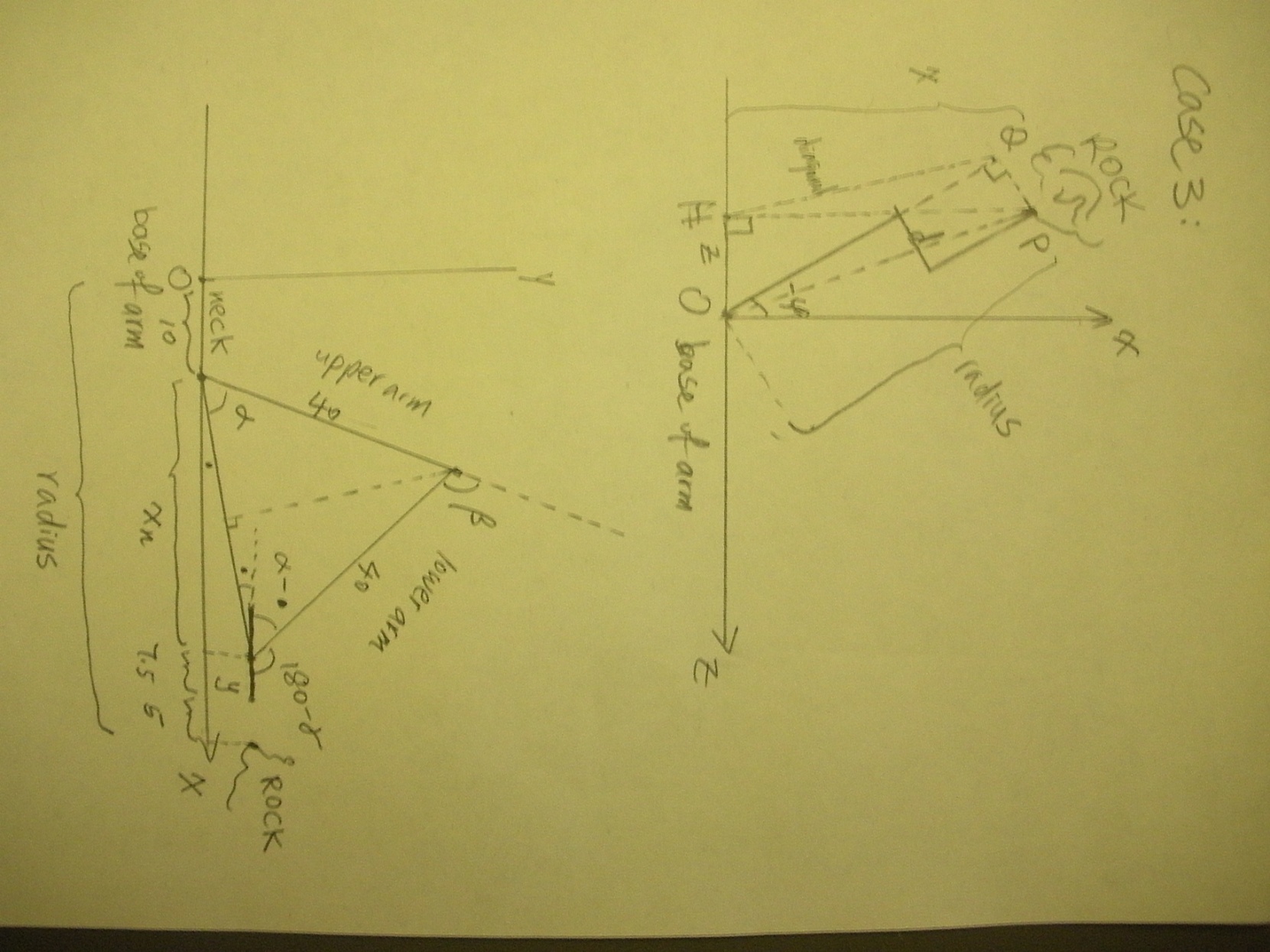
In case 3, we have z to the left of the x axis, so much of the calculation remains the same, but some signs we reversed:

Again we have OHPQ is a cyclic

Quadrilateral, because of the 2 right angles at Q and H. We first find radius OQ, then apply Ptolemy’s Theorem and Cosine Law to find φ, which is negative, because we (or matlab) has defined the axis and rotation such that when the arm is pointing along x axis, φ is 0, and when it turns to the left, φ is negative. We have:

And radius is given by the same formula.

The second case is when z = 0. Notice that we can no longer divide by z, as is done in the formula above. The geometry is the following:

Step 2: Now having settled yaw angle and radius, we look at the vertical (x-y) plane at the pitch angle, and see what angles of the other joints are required to have the drill head reach reference position. Firstly, we recognize that the radius calculated is the distance “along” the arm in the forward direction, but includes the length of the neck piece, half the length of the manipulator, and the 5 cm from reference position to the rock. So we subtract these out to find the *net* x-distance, called xn: xn = radius – 10cm – (15/2)cm – 5 cm = radius – 22.5 .

Note: in this diagram, the x axis is NOT the same x axis as before; it is simply the axis ALONG the direction of the arm. It is only equal to the x axis when neck yaw angle = 0. It is called the x axis here, perhaps confusingly, because most of the time we are dealing with arms pointing straight forward, and it is convenient to decompose motion into components of “along the arm” and “perpendicular to it”. As the reader will see, this different definition of x axis makes no difference in the calculations to follow.

We subtracted all these components off radius to get xn, because xn is what’s relavant in calculating angles of the upper arm, lower arm, and manipulator.

It is important to note how the radius in this diagram corresponds to the radius defined and calculated in the previous part. Convince yourself that they are indeed the same distance.

So the problem at this stage is: given xn, y, and arm lengths, find joint angles .

The result immediately follows from the diagram:

So

Note: is the angle labelled with a dot in the diagram.

* 1. **Generating Angle Signals**

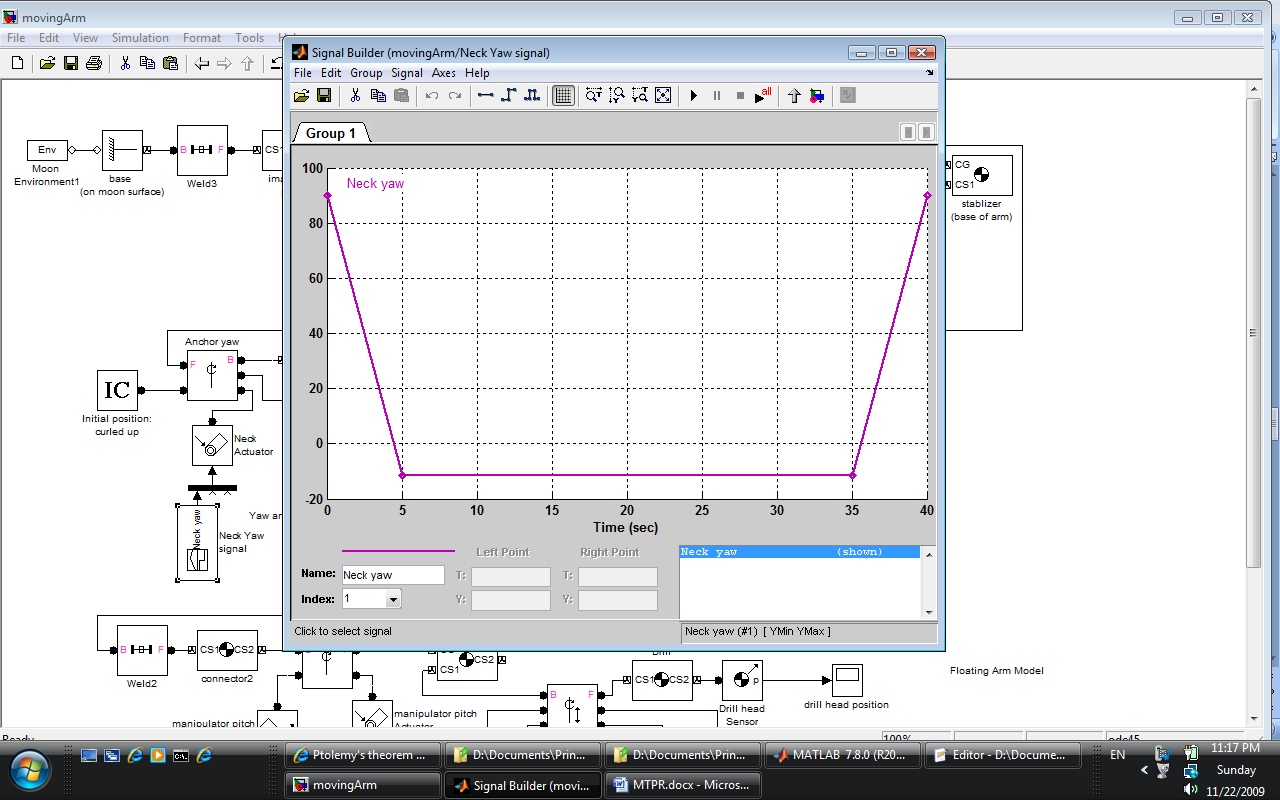
So for given coordinate of rock position (x, y, z) relative to base of arm, we have caluclated the required joint angle at the end position. Now the question is how to reach there, from the curled up position.

We need to take into account the phyiscal limit on movements of links. But even then, there are multiple feasible plans. We came up with the motion plan described below to transfer the arm from its curled up position to the reference position with angles just caluclated, with the following considerations in mind:

* This transfer plan is modular: each joint moves into position sepaerately to the extent possible, so easy to control.
* This transfer plan does not involve any part of the arm going too low in the y direction, which would mean hitting the ground.
* This transfer plan avoids hitting the vehicle too.

Transfer plan: The arm will start from the curled position, extend out to engage target, drill into rock, take pictures, then curl back up, in 40 seconds. This time interval can be easily changed as need arises.

Stage 1: arm rotates outward from curled up position to face forward, in the x-direction. This correpsonds to only a neck yaw movement from 90 degrees to , at uniform speed, from t = 0 to 5 sec. At the end, from time 35 to 40, the reverse aciton aoccurs. So our windown of action is now restricted to t = 5 ~ 35 sec, during which the neck is to remain stationary.

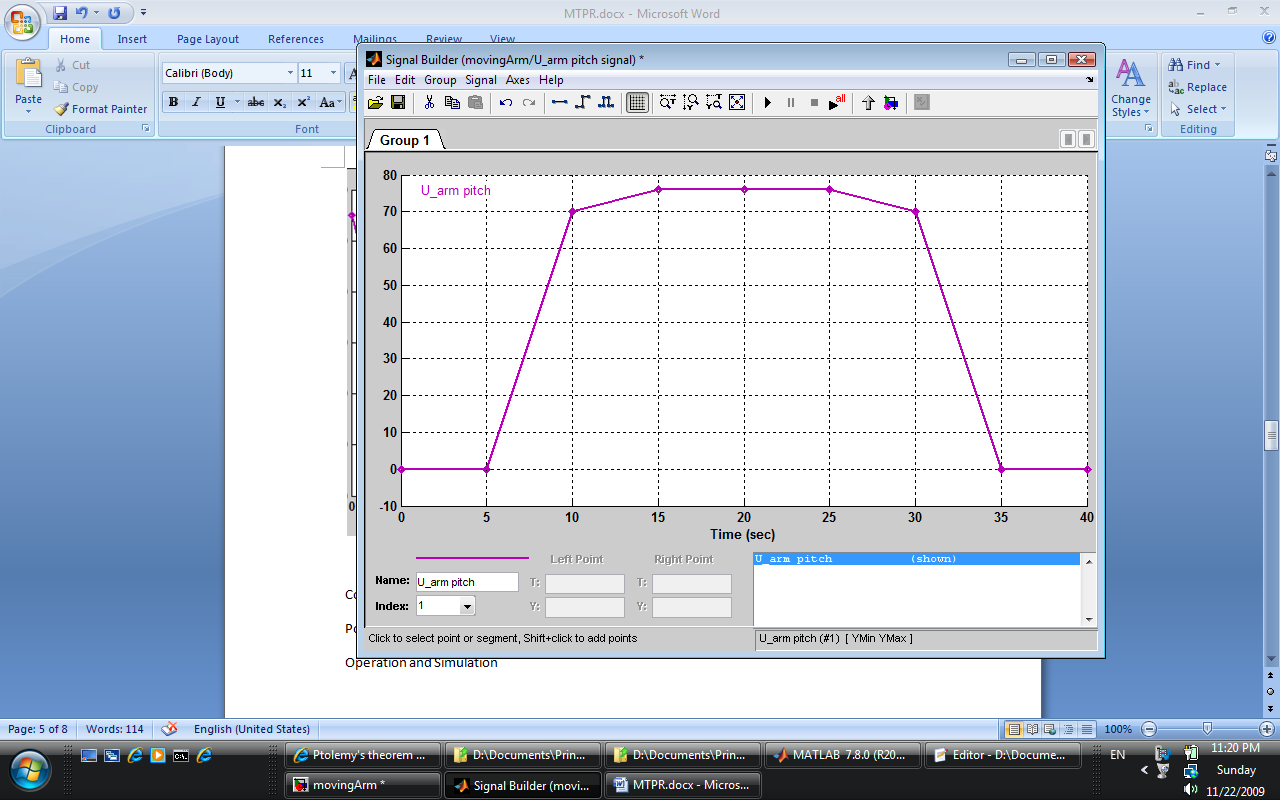
The required yaw angle for the neck yaw joint for the 40 sec duration is displayed below:

90

Stage 2: with the neck holding its position, the upper arm raises from flat to 70 degrees up (near its limit), to facilitate later extension of lower arm (without hitting the ground). This occurs at uniform speed from time 5 to 10, then the reverse action occurs from time 30 to 35. So our action window has been reduced to the interval t = 10 – 30 sec.

φ

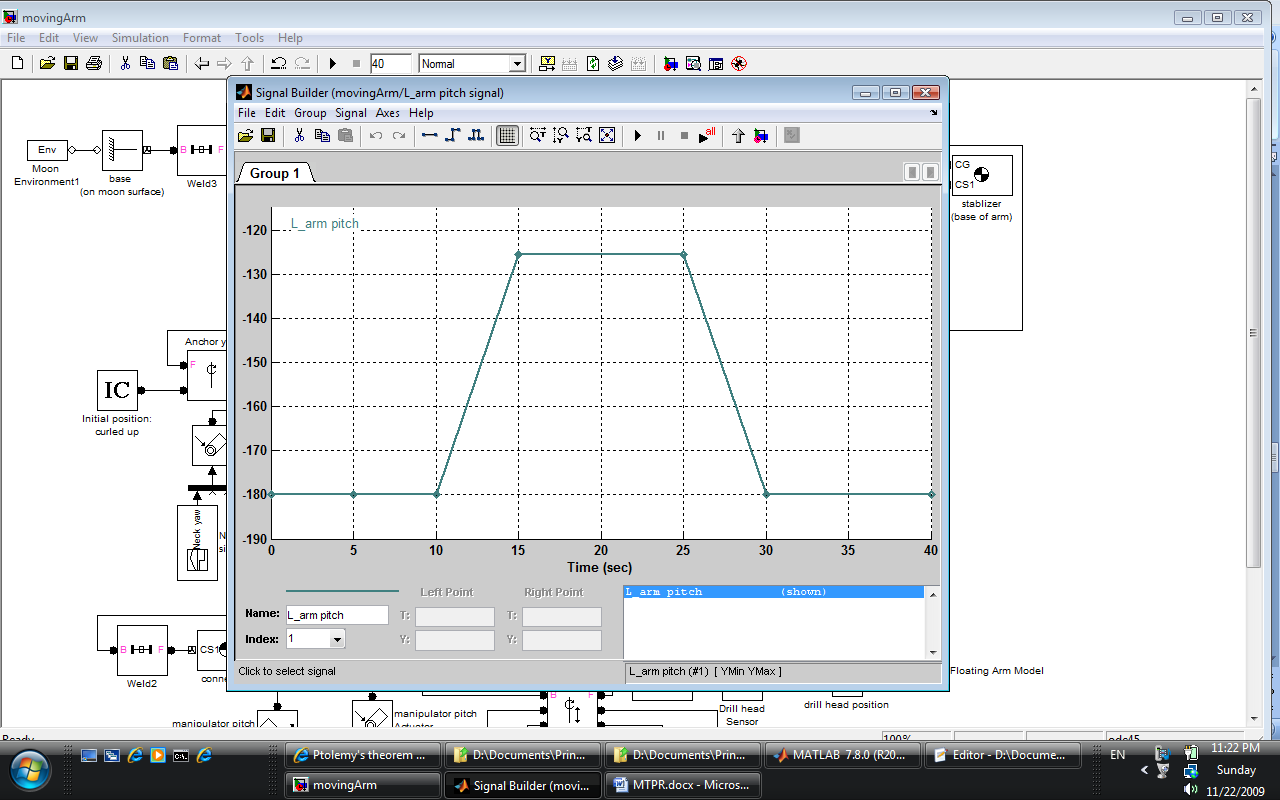
Stage 3: now the upper arm and lower arm have to move together. As the lower arm extend out from underneath the upper arm, the upper arm also extends forward but the amout needed. From time t = 10 to t = 15, upper arm will move from 70 degrees to α, its desired angle at reference position, with uniform speed. During the same window of time, the lower arm will move from -180 to β, its desired angle at the reference position, with uniform speed. So by the end of 15 sec, distal end of lower arm is in position for drilling. We still have to adjust to manipulator position later, before drilling. From t = 25 to t = 30, the reverse action occurs for the upper and lower arms, which retract to their orignal position at t = 10, from reference position. So the window of action is reduced to t = 15 ~ 25 sec.



α

70

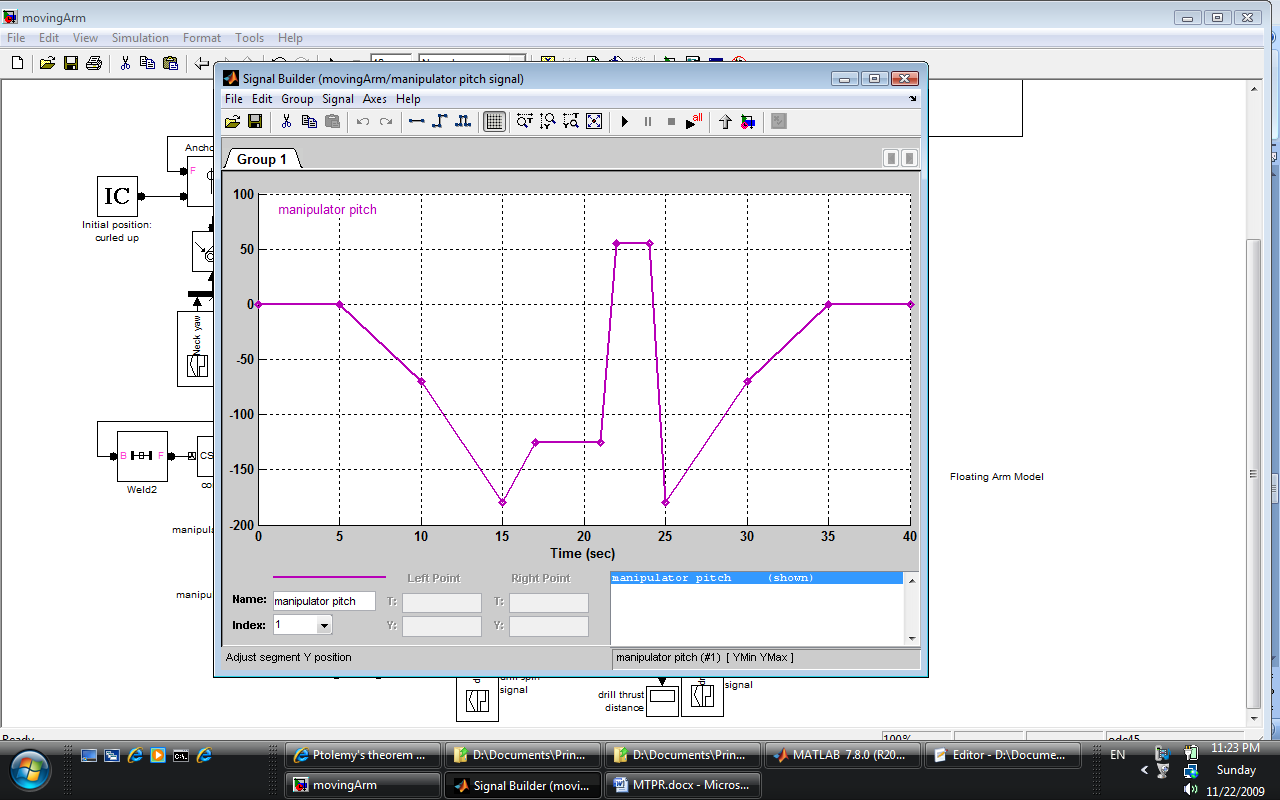
Note that α is usually smaller than 70 degrees.



β

-180

Stage 4: This is the movement of the manipulator, and it is the most complicated of these stages, mainly before it has to move in sync with the arm parts to avoid venturing too low and hitting the ground, and also it has to move into position for picture taking and drilling. It’s action starts from t = 5: as the upper arm raises to 70, it has to extend by 70 (i.e. goes from 0 to -17 degrees) to remain parallel to ground. Then as the upper and lower arm reach out together, it has to extend further to remain “approximately” parallel to ground; it extends uniformly at the speed needed to transfer the angle from -70 to -180 (parallel to lower arm as in curled up position but with opposite orientation) as time goes from 10 to 15 sec. Then, depending on β, the manipulator has to rotation enough (by γ) to be parallel to ground for drilling, which is assumed to take 4 seconds in this model/simulation. This part can of course be extended to minutes if desired. Afterward, it rotates by 180, from -180+ γ to γ, to bring imager to front for picture taking, which is assumed to take 2 seconds. Then it rotates back to its position at time t = 15, and the same action unwinds, to bring it back to the curled up position.



-180

0

-70

-70

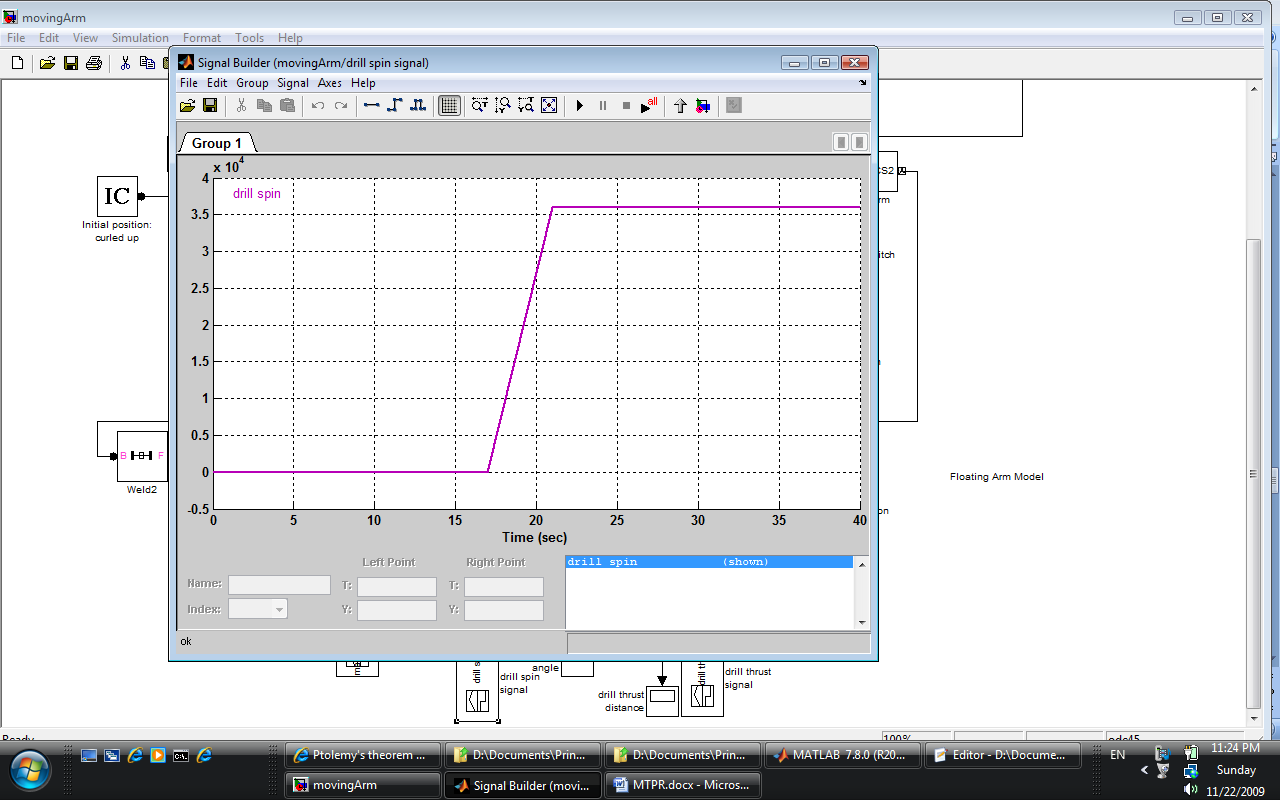
-180

γ

-180+γ

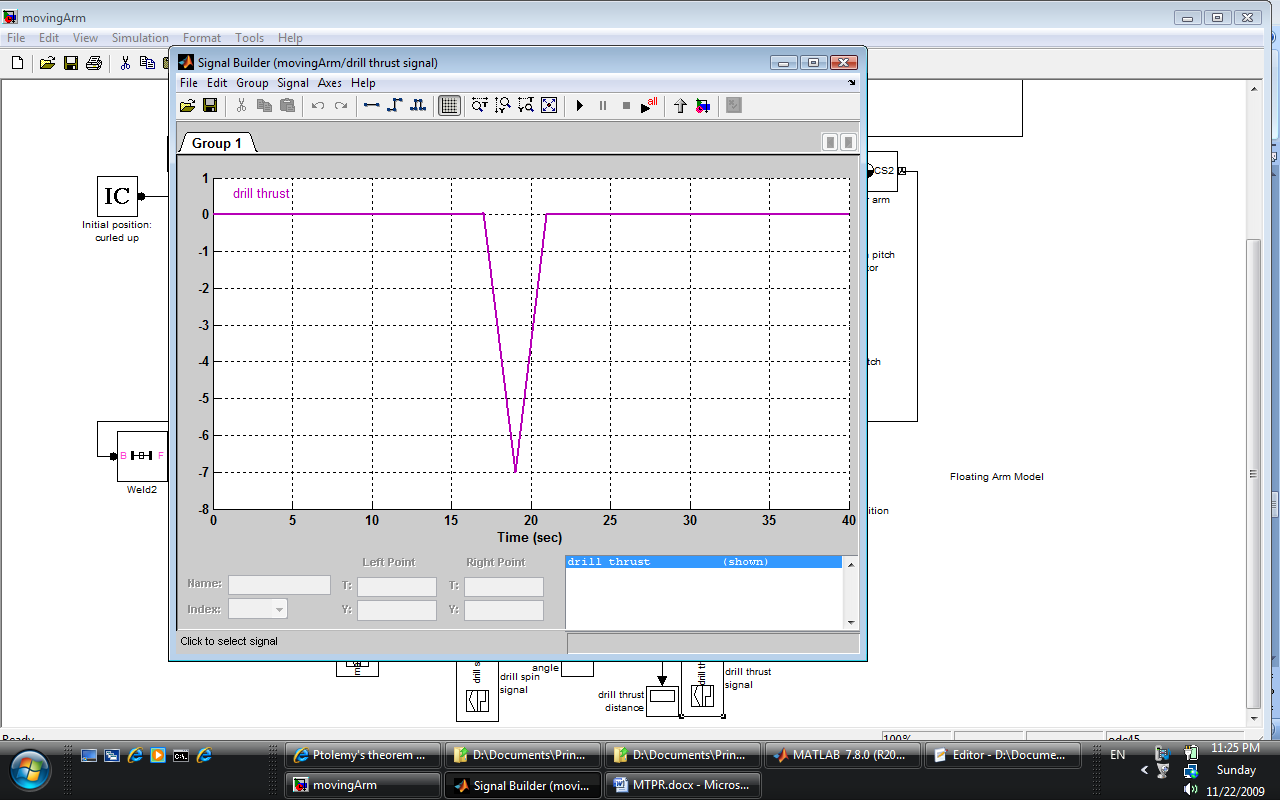
0

Stage 5: Drilling occurs from time 17 to 21 sec, the drill head moves forward in the first 2 second, and retracts in the second 2 seconds. The drill motion includes spinning as well as thurst. The signals of drill action are shown below:



Large multiple of 360

0

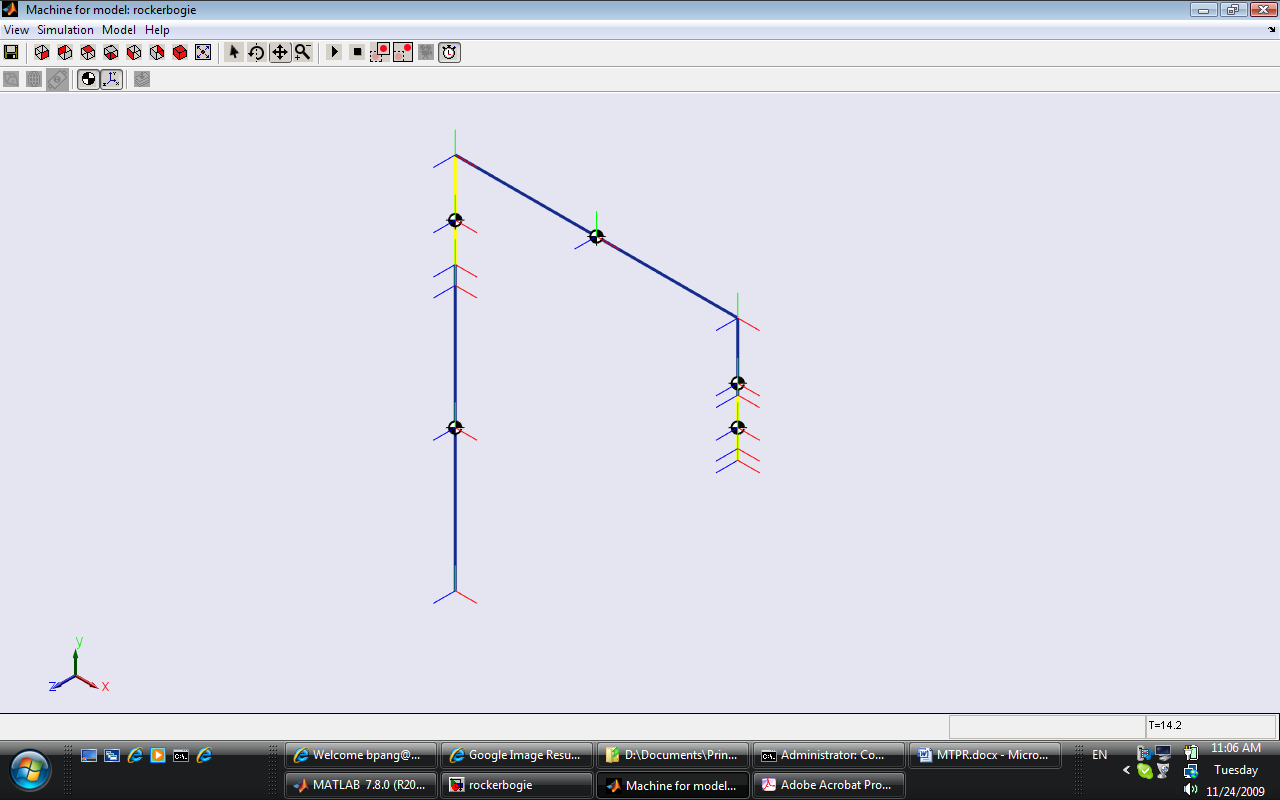


5 cm + desired depth

* 1. **Rocker Bogie**

The rocker bogie is a spring-like mechanism that provides damping as the rover traverses uneven terrains. As the arm extends outward and perform actions, we would expect the weight (center of mass) of the car to shift, thus causing the rocker bogie to move, which would make the base of the arm unstable. The way in which the base of the arm bounces depends on how the arm moves out, and is hopelessly difficult to calculate. In modeling the motion of the rocker bogie, we make the following simplifying assumption: the base of the arm only moves up and down.

Then, our strategy is the following:

If we cannot know the motion of the rocker bogie precisely, we can model it as random noise, of amplitude no larger than 2 cm, in the y direction. To change the joint angles to accommodate for this noise would be very difficult, so instead we introduce a stabilizer device preceding the base of the arm. This stabilizer is a short cylinder positioned vertically on a prismatic joint, and as the chassis of the rover moves up and down, the stabilizer senses that and moves in the opposite direction, so as to leave the base of the arm (which is attached to the center of the stabilizer) in the same absolute position, (0, 0, 0). This is easily achieved by attaching a sensor to the bottom of the rover to sense its distance to the ground, and feed the *negative* of that signal to the stabilizer. So we have effectively cancelled out the action of the rocker bogie, leaving our prior analysis intact.

chassis

Moving piece mimicking motion of rocker bogie

Short overhang piece

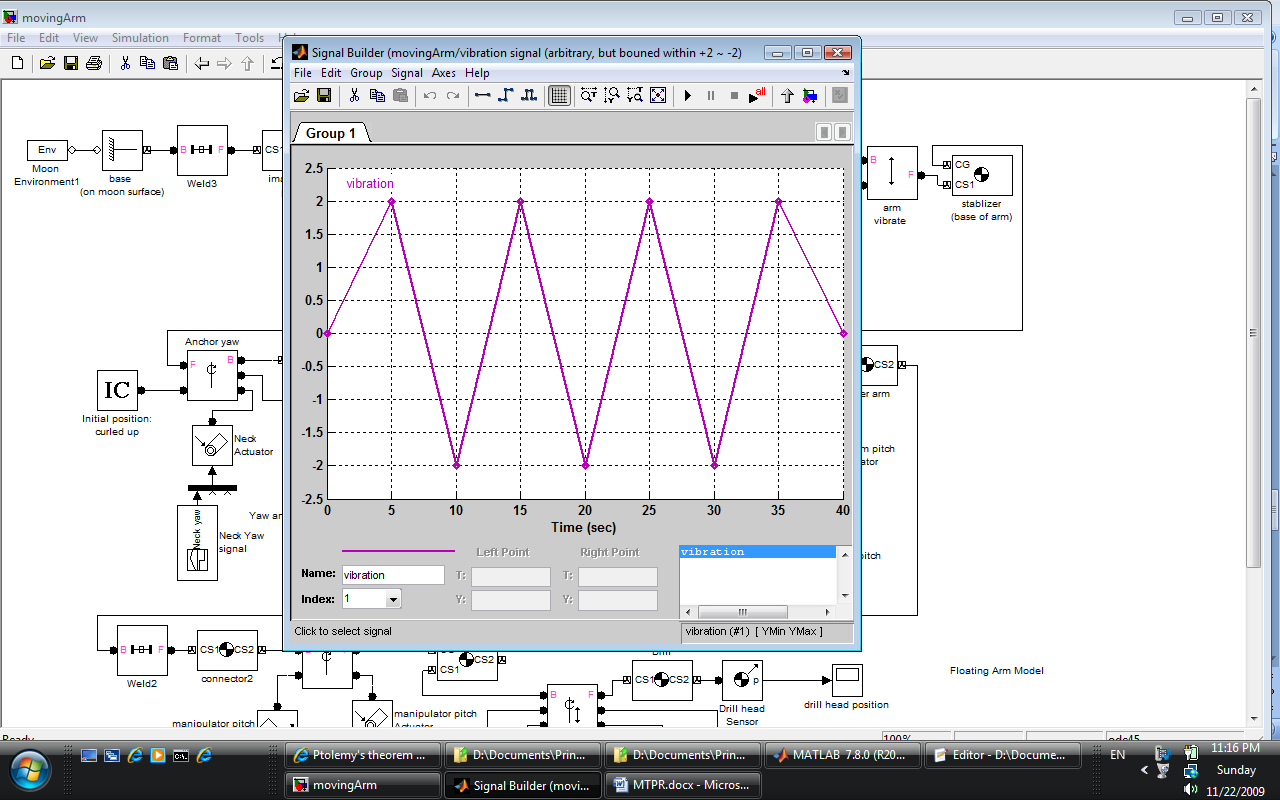
Stabilizer moving up and down to adjust

Imaginary pole

Ground on surface of moon

With such design, we don’t care how the rocker bogie moves anymore, as long as it remains within the movement bound of the stabilizer, which is 2 cm up and down, in this case.

For example, we can input the following user-selected signal for motion of rocker bogie:

****

2

-2

And we just have to reverse this arbitrary signal and feed it to stabilizer to keep the base of arm fixed.

Of course, we can easily extend this model to allow motion of rocker bogie in x and z directions as well, and it will similarly be counteracted by a (more complicated) stabilizer.

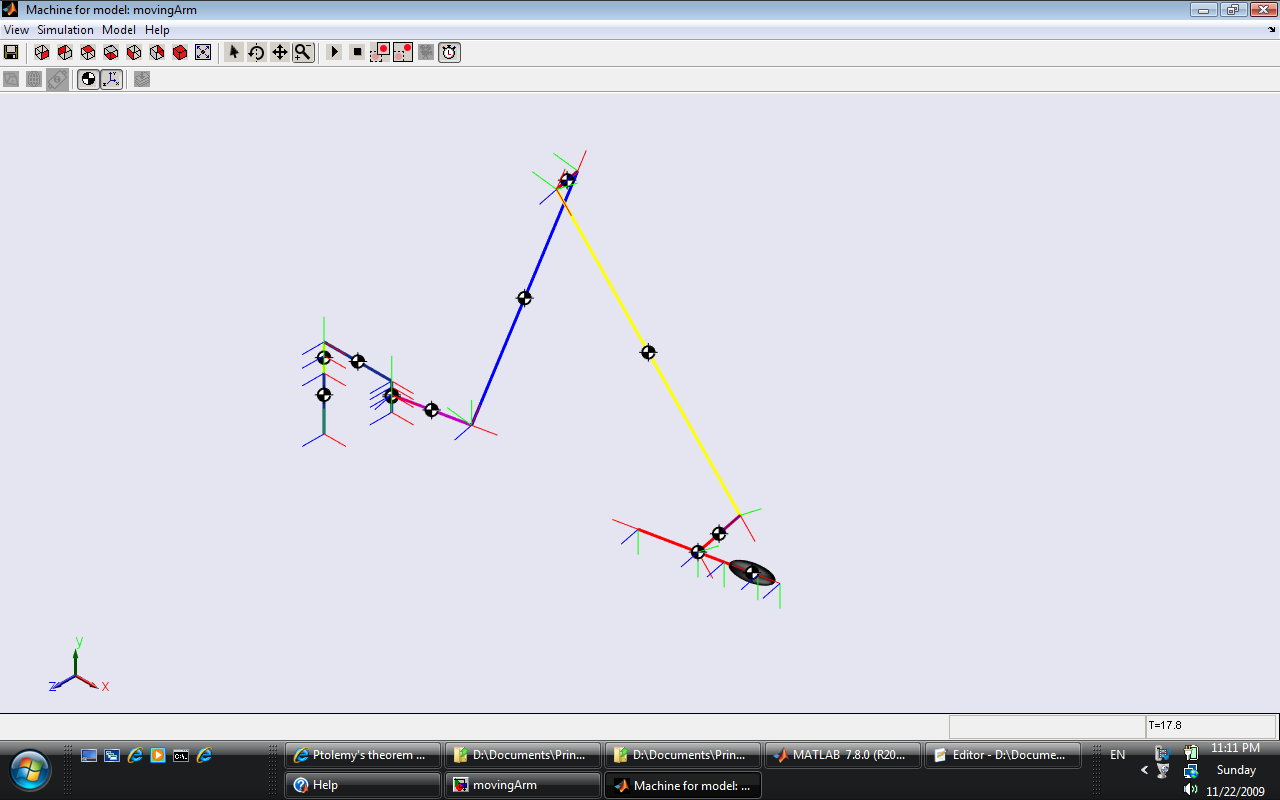
1. **Control Logic (Garrette)**
   1. Algorithm
   2. Physical Aspect
   3. Treatment of Error
2. **Arm in Action**
   1. **Simulation**

The 40 second simulation shows the arm moving out from reference position, engaging target which is specified by (x, y, z) coordinates of rock with base of arm at (0,0,0), performing actions (drilling and picture taking), and retrieving back to curled up position.

Meanwhile the rocker bogie is moving about with the saw tooth shaped signal shown before. This is a snap shot of the simulation, when the drill head is spinning forward.

The rock is assumed to be at (60, 5, 0). Depth of drilling is set to be 2 cm.

Simulation parameters used are: sampling time = 0.05 sec.



A body sensor connected to the drill head shows its position throughout the simulation:

Yellow = x position,

Purple = y position,

Cyan = z position.

Reference position, at 55cm

Tip at 62 cm, max

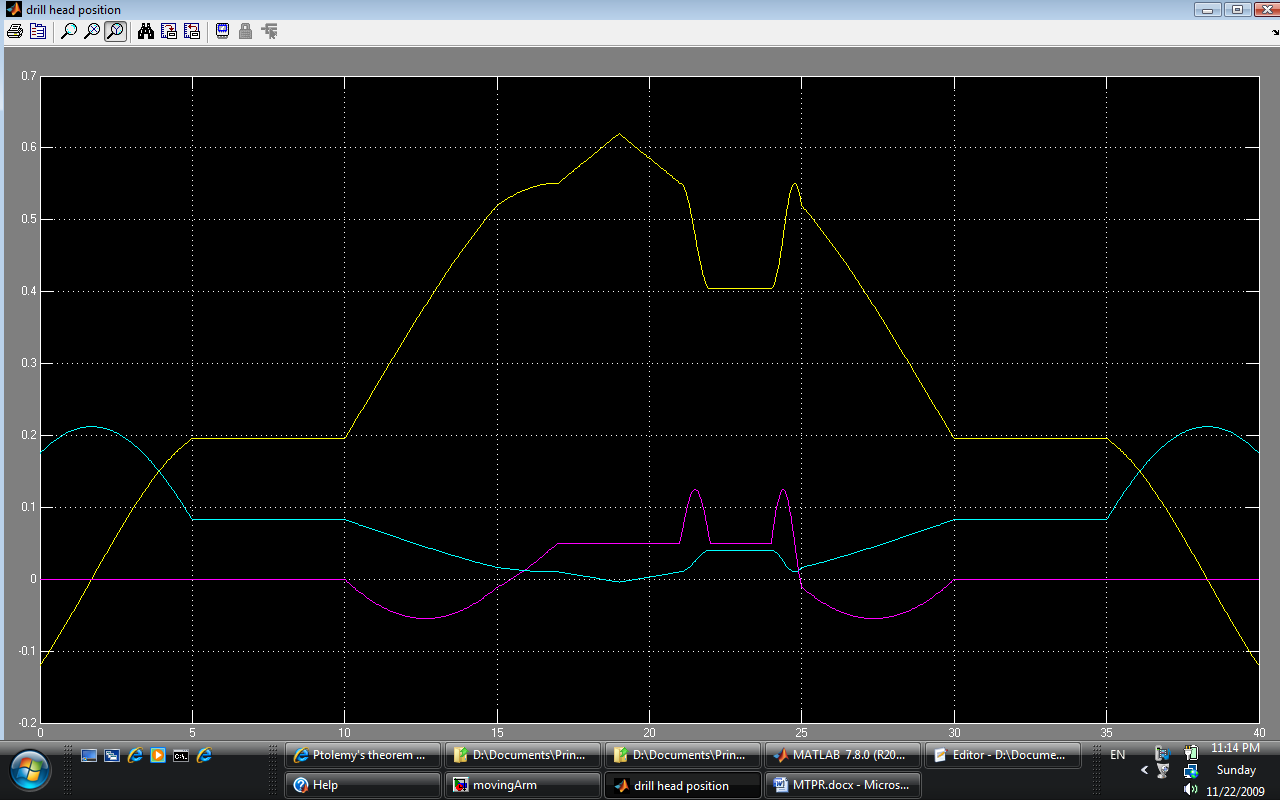
Rock at 60cm

Drill out

Drill in

Picture

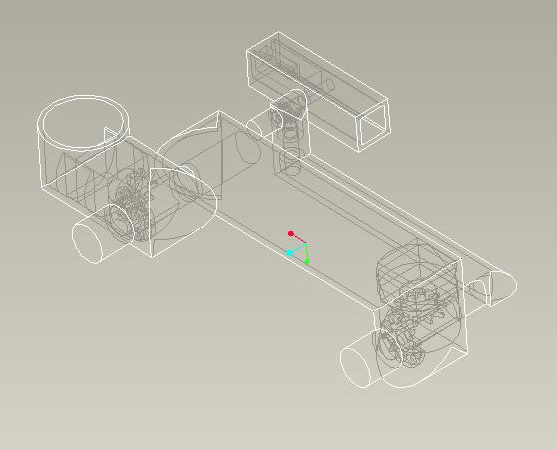
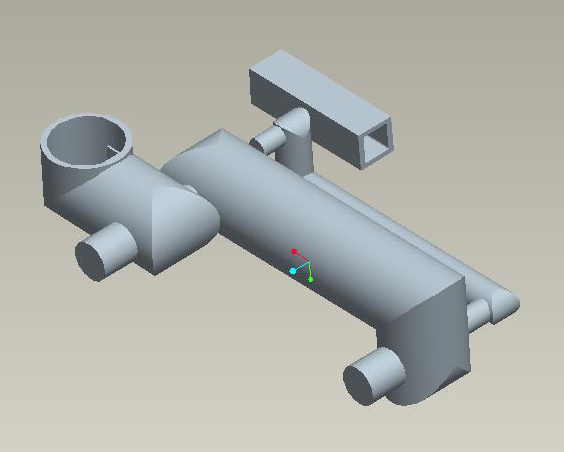
taking

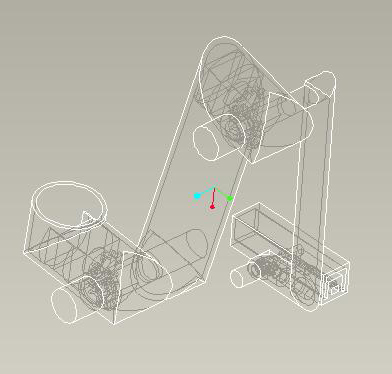
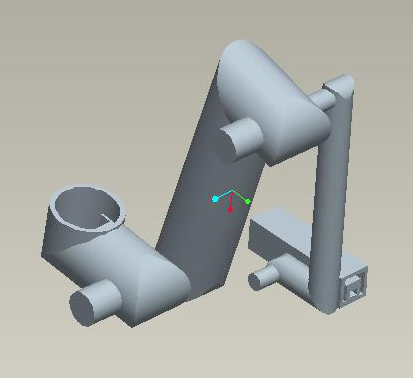
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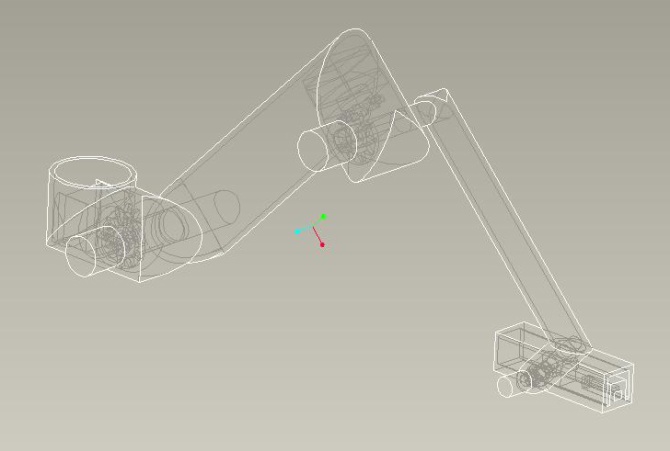
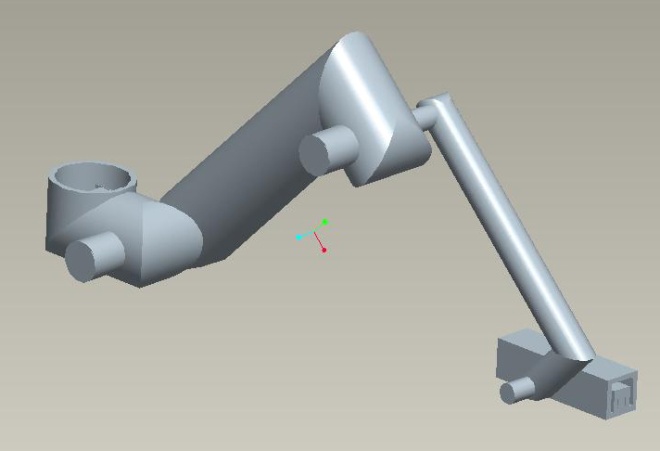
Manipulator spin

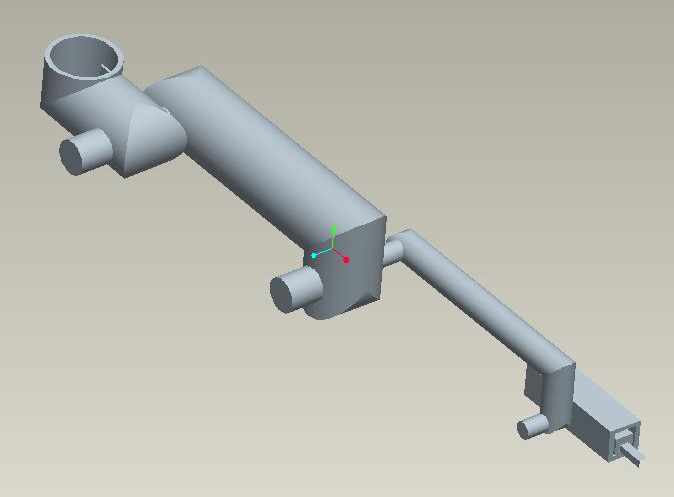
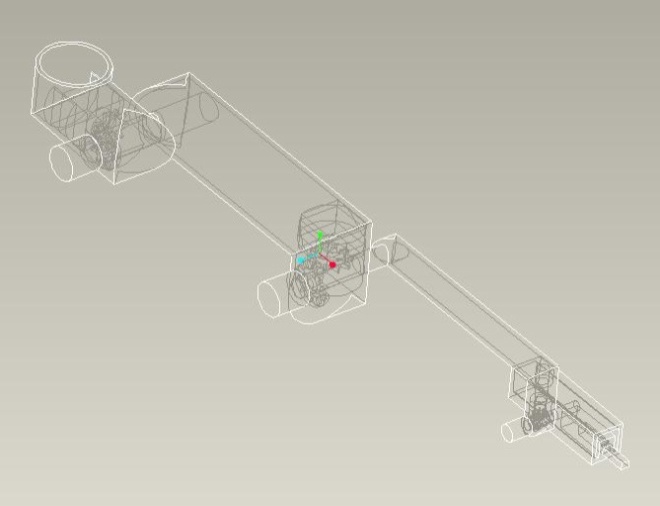
Manipulator spin

Never venture below 5 cm

* 1. ******Snapshots of Unfold Arm with Actual Parts**



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****

**7.3 Power Consumption (Garrette)**

1. **Major Pitfalls**
2. **Feasibility and Future**

(use equations, figures, tables, graphs, citations, and animations)

(cite all tables/equations/graphs borrowed. )

(format tables/graphs in appropriate manner to make information easy to understand. Explain their significance. )

1. **Conclusion**

Estimation of cost

# Works Cited

# Appendix: Matlab code for Angle Calculator

function [alpha beta gamma phi] = CalAngle(x, y, z)

%% x = forward distance from base of arm to rock surface

%% y = vertical distance from base of arm to rock surface

%% z = lateral distance from base of arm to rock surface

% alpha = inclination of neck-upperarm joint

% beta = bending down of upper-lower arm joint

% gamma = angle between lower arm and manipulator

% phi = yaw of anchor joint

% L = length of upper arm and lower arm

% N = length of neck

% R = distance from CG of manipulator to tip

% REF = 5 cm, specified in the problem

% OFFSET = lateral offset of the tip of drill from arm base

L = 40;

N = 10;

R = 7.5;

REF = 5;

OFFSET = 12;

radius = (x^2+z^2-OFFSET^2)^0.5;

xn = radius - N - R - REF;

beta = -180 + 2\*asin((xn^2+y^2)^0.5/2/L)/pi\*180

alpha1 = atan(y/xn);

alpha2 = acos((xn^2+y^2)^0.5/2/L);

alpha = (alpha1 + alpha2)/pi\*180

gamma = (alpha2 - alpha1)/pi\*180

diagonal = (x\*radius + OFFSET\*z)/(x^2 + z^2)^0.5;

if z > 0

phi = 90 - acos((radius^2 + z^2 - diagonal^2)/(2\*radius\*z))/pi\*180

elseif z == 0

phi = -asin(OFFSET/x)/pi\*180

else

phi = acos((radius^2 + z^2 - diagonal^2)/(2\*radius\*abs(z)))/pi\*180 - 90

end

end