

## Robotics: Science and Systems I

### Lab 2: Motor Control and Chassis

**Distributed: February 11, 2015 at 3pm**

**Due: February 23, 2015 at 3pm**

## Objectives

In lecture, we learned about motor characterization and motor control: how to modulate the power supplied to one or more electric motors in order to achieve some desired behavior (typically, a specified velocity or velocity profile in time). Your specific objectives in this lab are to:

- Begin assembly of your robot body;
- Understand how to characterize an electric motor;
- Read a motor's performance specification, apply power to the motor, use sensing to estimate its rotational speed, and develop a control algorithm allowing the motor to be commanded to run at any desired speed.
- Use your characterization to implement a two-wheel motor controller enabling you to command your robot to translate and rotate.
- Establish coordinate systems for the robot and the lab, measure "ground truth" (i.e., the robot's physical motions with respect to some world coordinate frame), and evaluate the accuracy of your robot's commanded motions.

In this lab you will craft feed-forward, proportional velocity-error (P), and integrated velocity-error (I) controllers for a single wheel and differential velocity control algorithms for PWM motor control. You will gain physical intuition about how motors behave under load. These skills will enable you to get your robot chassis moving around in a controlled way.

## Physical Units

We will use MKS (meters, kilograms, seconds, radians, watts, etc.) units throughout the course. We insist that you do so as well. In particular, this means that *whenever you state a physical quantity, you must state its units*. Also show units in your intermediate calculations.

## Skill Point Allocation

Each team member should assess his or her skill levels **as of the start of the lab** in each of the following areas, on a scale of 1 to 5 (1=Not at all proficient; 2=slightly proficient; 3=reasonably proficient; 4=very proficient; 5=expert):

- **Mechanics:** How proficient are you at mechanical assembly?
- **Motors:** How proficient are you at motor characterization and control?
- **Java:** How proficient are you at programming in Java?
- **Motion:** How proficient are you at crafting robot motion
- **Version Control:** How comfortable are you using a Version Control system? algorithms using odometry?

Each team member can add his or her self-assessment to the respective Wiki Avatars, in the provided Lab 2 section "Beginning of Lab."

## Materials

In addition to the Motor Control Lab Procedure that you are reading now, you should have on hand the following:

Paper handouts:

- Motor Specification Sheet (available on course web site)
- Shaft Encoder Specification Sheet (available on course web site)
- Battery safety handout
- Subversion source code control handout

In your bin:

- 1 piece of pegboard
- 2 motors
- 2 solid wheels
- 2 caster wheels on mounting plates
- 2 motor screws
- 3 15" aluminum 80/20 beams
- 2 13" aluminum 80/20 beams
- 2 5" aluminum 80/20 beams
- 6 brackets (2 L-brackets, 4 angle brackets)
- 42 1/4-20 x 1/2" hex bolts and sliders
- $\mu$ Orc board, ethernet cable, AC power adaptor
- 1 lead-acid battery and cable with terminal connectors
- Hex keys
- Tape measure
- Sharpie marker
- Masking tape for marking floor grid

## 1 Configuring your Netbook and Workstation

Both the netbook and the workstation run Linux, specifically Ubuntu 11. Each has an account setup for the `rss-student` user with a default password. As a group, you need to decide on a password to replace the default password.

1. Decide on a common password for your group. This password should be strong: include numbers and letters, upper- and lower-case, and a symbol or two. Both your workstation and netbook have network connections to the outside world that can be exploited by hackers. A weak password leaves your computer more likely to be compromised.
2. Log-in to your netbook using the `rss-student` account and the default password provided by the course staff.

3. Open a terminal window (Application → Accessories → Terminal) and run `passwd`. The `passwd` command will ask you to verify your old password and then ask for your new one.
4. Log-out and re-log-in to test your new password.
5. Repeat steps 2–4 for your workstation.

*Deliverables: None.*

## 2 Creating a Team Wiki Area and Member Pages

*It is the digital projection of your mental self.*

— Adapted from Morpheus, *The Matrix*

The RSS wiki is where you will submit many of your assignments and a good source of information about many aspects of 6.141. The wiki is only accessible with an Athena certificate. When you first access the wiki with your Athena certificate, an account will automatically be created and you will be automatically logged-on. Until you inform the course staff that you have created an account on the wiki, you will be unable to edit it. To prevent your teammates from gaining access to your certificates, you may use Firefox’s password manager to protect them. Additionally, so that each team member can log-into the wiki independently, you may create a Firefox profile for each teammate.

1. Configure Firefox to run its profile manager at start-up: *On the workstation*. Create an icon on the Desktop which runs `firefox -p`.
2. Create Firefox profiles for each group member: Start Firefox by left clicking on the Firefox icon in the GNOME Panel. You’ll be presented with the Choose User Profile dialog. Use the Create Profile button to create a profile for every group member. Once each group member has a profile, click Exit.
3. Start Firefox using the link in the panel at the top of the screen and then select one group member’s profile in the Choose User Profile dialog. Then, click Start Firefox.
4. Enable the Firefox password manager: In Firefox, select Edit → Preferences and then select the Security icon at the top of the resulting Firefox Preferences dialog. Click to select the ‘Use a master password’ check-box. Enter a unique and secret password for the active profile. Click OK. Close the Firefox Preferences Dialog.
5. Obtain an Athena certificate: Navigate to <https://ca.mit.edu/ca/> and follow the instructions.
6. Log-into the wiki: Navigate to <https://courses.csail.mit.edu/rss/wiki/>. Ignore the security warning. Then, if asked, provide your password from Step 3 and instruct Firefox to access the site with your newly acquired Athena certificate. Once you have access to the wiki, you’ll see that it knows your identity as indicated by the display of your name near the top right of the page.
7. Close Firefox and repeat Steps 2—6 for each teammate. Leave your last teammate logged-into the wiki.
8. Repeat Steps 1—7 on your netbook.
9. Give a staff member a written list your full names as they appeared in the upper right of the wiki when you were each logged-in. The staff will then proceed to give you write access to the wiki so that you can continue with the next step.
10. You will see that each group has a generic team wiki page, each containing a generic page for each team member. It is now your responsibility to populate your team and member wiki pages.
11. We recommend that you start by working on the team wiki page while you’re all in the lab. Make sure that the following sections are set up and formatted to your team’s tastes:
  - Rename your team to something more epic than “Team N” - you can change this again later, of course, but we prefer awesome names to the placeholders we provide.
  - Upload a fitting picture to represent your team. For example, you could use your team’s favorite robot. Add it to your team page. You can use Google Image Search to find a picture; we just want you to have practice uploading files to the wiki.

- You can leave the team inventory alone for now - you'll place completed assignments, uploaded image links, and your weekly wiki reports into the appropriate pouches later in the class.
  - Fill out the Availability section in a manner that allows for clear, concise viewing of each team member's strict time commitments. A sample format is provided - feel free to use it, embellish it, or completely redesign it; so long as we know when you're free, we'll be happy.
  - Lastly, we invite you to fill out a bio for your team wiki page. This is a great place to jot down your collective background in robotics, recall your biggest kills, or remind the Lab Authorities that this class is serious business (not the glorified gaming experience they seem to think it is).
12. Next, we can move on to the key parts of the wiki. Each member of your team is responsible for his/her own member page, and all of them will need to be updated regularly, so save the URLs!
- First off, fill out the General Information section with your name, E-mail address, mobile phone number, specialization (hardware, software, firmware, kitchenware, etc.). If you're feeling creative, add any other key attributes that you feel should be recorded. Please keep the contact information (at least) up-to-date as the year progresses.
  - Next, update the Saved Progress section with the hours that you have worked this lab session. All future hours that you put into this class should also be logged here (lectures excluded). We will be using this chart to keep track of how long assignments take you and your team, so be sure to update it regularly.
  - The personal inventory is for any uploads that you would like to have access to as you work through the class. This includes the existing pouches for your reports and reflections, as well as additional space for extra supplies you'll need on the journey ahead.
  - The skills section is where you'll record your skills at the beginning and end of each lab. Relevant skills will be outlined in each new lab handout. There is a chart for this lab included, so you can practice by incorporating values in for your relative proficiency with each skill **as of the beginning and end of this lab** in each of the following areas, on a scale of 1 to 5 (1=Not at all proficient; 2=slightly proficient; 3=reasonably proficient; 4=very proficient; 5=expert):
  - Ignore the Achievement section for now; if you redesign your page, we suggest that you leave space for it somewhere. The staff will populate this section as the semester progresses.
13. That's it! Once your team has completed its team wiki, and each of your team members has created and filled out his or her own member page, you're ready to venture forth.

*Deliverables: Show a staff member your team wiki entries. He or she can then check you off for your work.*

### 3 Establish Your Wiki Area for this Lab

Each RSS Lab requires a team-authored set of wiki materials. Create space for these in your team's Lab Materials area at [http://projects.csail.mit.edu/rss/wiki/index.php/Main\\_Page](http://projects.csail.mit.edu/rss/wiki/index.php/Main_Page). Title the page with the lab name and use the Wiki formatting syntax to post and organize any question responses, images, video clips etc.

As you work through the lab, add text and upload screenshots and photos to the wiki. In particular, be sure that *every italicized question and deliverable throughout the lab is answered on the wiki*.

### 4 Assembling the Chassis

*The road to success is always under construction.*

— Lily Tomlin

You will now assemble the robot chassis. You may copy the staff's exemplar robot, follow the instructions given below, or perform some combination of the two. Some steps can be carried out in parallel. In general, defer tightening



Figure 1: Rollbar assembly: Put bolts and sliders on the L-brackets.



Figure 2: Slide the 5'' segments of 80/20 onto the L-brackets.

bolts until recommended by the handout; this will make your life easier when sliding together and adjusting the 80-20 segments.

1. Assemble the rollbar (see Figure 3).
  - (a) Put four 1/4-20 bolts and sliders on each of the L-brackets, as shown in Figure 1. Do not tighten down the sliders yet.
  - (b) Slide the L brackets onto a 15'' 80/20 beam. Then slide the two 5'' 80/20 beams onto the L-brackets, as shown in Figure 2.
2. Put 1/4-20 bolts and sliders on all the angle brackets, as shown in Figure 4. Do not tighten them down.
3. Put eight 1/4-20 bolts in the pegboard - one in each of the front corners, one behind each of the two side notches, and two catty-corner on each of the back corners. Place sliders on the ends of the bolts, but again do not tighten them down.
4. Slide the 15'' beam of 80/20 onto the two front sliders, as shown in Figure 5. Slide two of the angle brackets onto the 80/20, placed so that their hypotenuses are facing inwards.
5. Slide the two 13'' beams of 80/20 onto the two sides of the pegboard. As you reach the notches on the sides, place an angle bracket there and slide the 80/20 onto it as well. Be sure to orient the angle bracket so that its hypotenuse is facing the back of the robot, towards you, as shown in Figure 6. As you reach the angle brackets attached to the 15'' beam, slide the side beams onto it as well.
6. Place one slider in the top groove of each side beam. Place two more in each of the outside side grooves, for a total of three sliders per beam.
7. Slide the last 15'' 80/20 bar onto the two back sliders, as in Figure 7. Put two sliders in the top groove.
8. Place the casters in the back corners, as in Figure 8. Attach with 3 1/4-20 bolts each, and tighten them down.
9. You can now tighten all of the 1/4-20 bolts on the chassis, except for those on the angle brackets intended for the roll bar.
10. Flip over the chassis, and attach the rollbar to the angle braces. It should look like that shown in Figure 9. Move the rollbar and braces as far forward as possible in the pegboard slots, and tighten all the remaining bolts.
11. Mount a motor to each side, using the two sliders placed there previously. Mount them directly underneath the rollbar, as in Figure 10. Try to ensure that your robot's motor shafts are collinear (why?).
12. Attach the wheels to the motors.

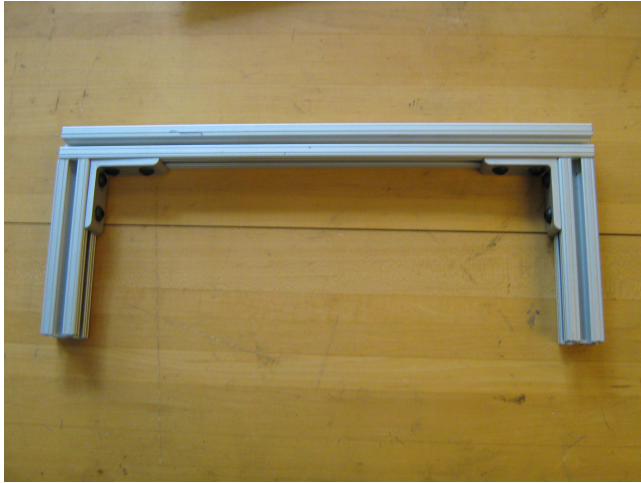


Figure 3: Completed rollbar.

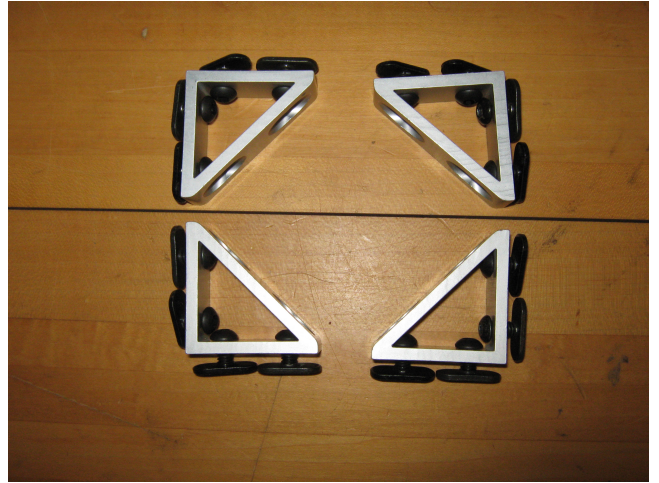


Figure 4: Angle brackets with sliders.

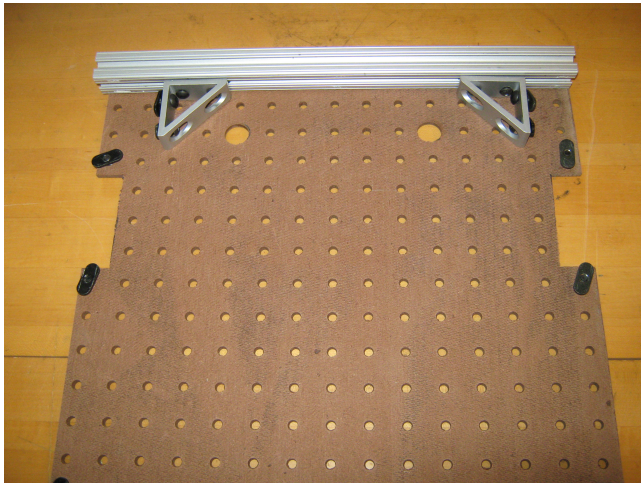


Figure 5: Slide 15" 80/20 and angle brackets onto front sliders. The placement of your sliders on the pegboard may look slightly different from that shown here.

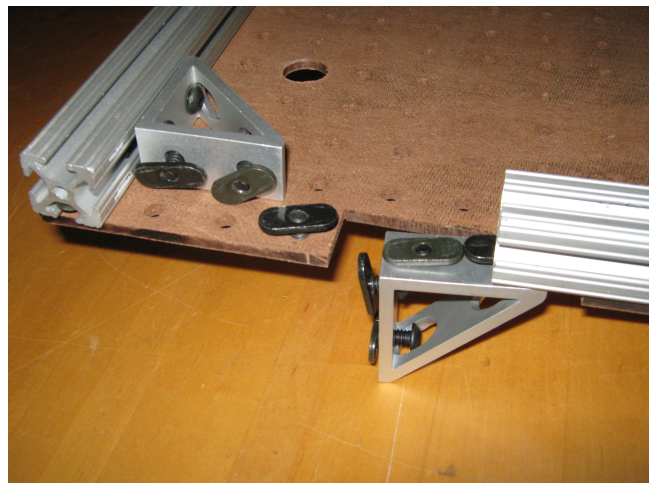


Figure 6: Slide the 13" 80/20 onto the sides of the pegboard, along with the angle brackets that will later attach to the rollbar.

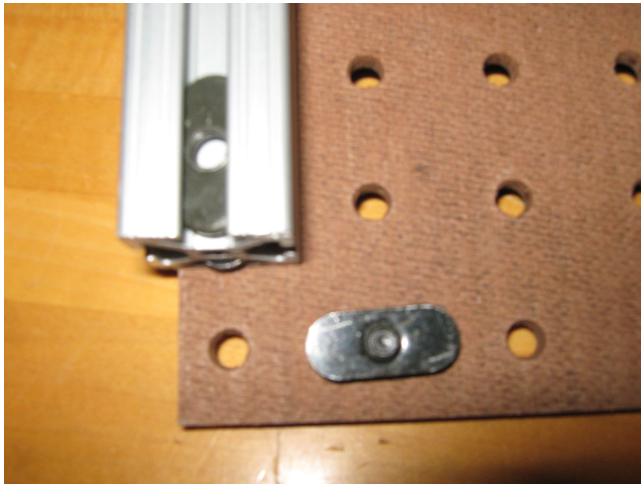


Figure 7: Slide the final piece of 80/20 onto the rear end of the robot.



Figure 8: Tighten the casters onto the two rear corners.



Figure 9: Attach the rollbar to the angle brackets on the top of the robot.

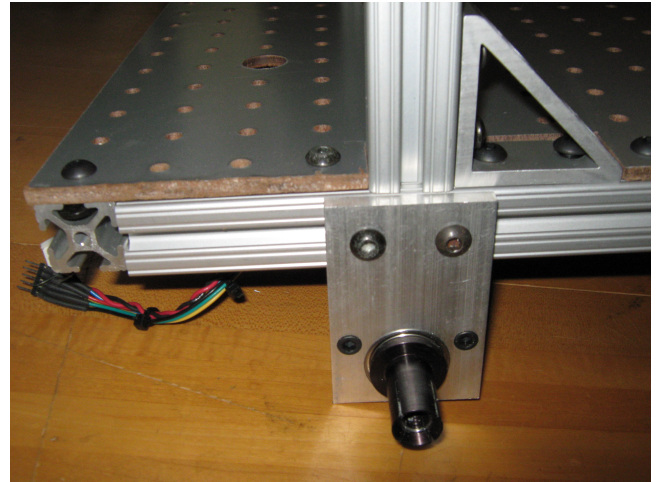


Figure 10: Attach the motors to the sides of the robot, directly underneath the rollbar.

13. Mount your  $\mu$ Orc and battery to the robot chassis. You may mount them wherever you like, but consider the effect of the battery's weight on the robot's driving performance. Leave room for the laptop behind the rollbar.

*Deliverables: Post to the wiki a brief discussion of your assembly process, especially steps that went particularly smoothly, were particularly difficult, or required substantial rework.*

## 5 Characterize the Wheel and Chassis Dimensions

*An attempt at visualizing the Fourth Dimension: take a point, stretch it into a line, curl it into a circle, twist it into a sphere, and punch through the sphere.*

— Albert Einstein

Measure and record your robot's left and right wheel circumferences and its wheelbase (distance between wheels), using the middle of each wheel tread as reference.

Connect the motors to the  $\mu$ Orc using the following steps:

1. Connect the left motor on MOT0, and the right motor on MOT1 (these are logically designated the left and right motor, respectively, in the supplied codebase).
2. Each motor has an internal encoder. Hook up the encoder for the left motor (in MOT0) to QuadPhase input 0. Take care to orient the connector correctly. Black is negative (ground) and red is positive. Repeat for the right motor, placing its encoder into QuadPhase input 1, again being careful about polarity. Do not power on your board until you have visually verified the polarity of these connectors using the exemplar robot as a reference.

*Deliverables: Add a photo of your robot. Record your measurements of the wheel diameter, wheel circumference, and wheelbase.*

## 6 SVN Tutorial

Subversion (often abbreviated SVN) is a software versioning and revision control system. In any context where you are writing code, documents, or working on any sort of digital files with multiple authors, SVN is a very useful system. It keeps track of iterative versions of files, allows simultaneous access by multiple authors, seamlessly joins edits made by multiple authors, resolves conflicts of overlapping content between authors, and allows for branching, merging, and reverting among revisions. It also allows you to keep consistently updated duplicates of files between multiple machines, which is especially convenient for ensuring that your workstation and netbooks reflect identical code.

Initially we will get you acquainted with SVN through the terminal interface, which you can access easily from any Linux or Mac machine. The instructions are geared toward access from the lab workstations and netbooks, which are running Ubuntu Linux, but we strongly encourage you to familiarize yourself with accessing Subversion from home. Windows users should look at PuTTY (<http://www.chiark.greenend.org.uk/~sgtatham/putty/download.html>), a SSH client which you can use to SSH into Athena (<http://web.mit.edu/dialup/www/ssh.html>) and subsequently run terminal commands from there, or you can try the more user friendly GUI interface of TortoiseSVN (<http://tortoisesvn.net>) which allows SVN versioning and management integrated directly into the Windows File Explorer.

This first part is a tutorial which goes over the basic functions and commands of SVN from the command line.

We will begin by checking out an existing repository, your group repository. Ask your TA/LA for your group's SVN password. On both your workstation and netbook individually, do:

```
mkdir ~/RSS-I-group
cd ~/RSS-I-group
svn co --username=rss-student https://svn.csail.mit.edu/rss-2015/groupN \
~/RSS-I-group
```

`svn co` checks out the latest file(s) from the repository.

Let's make an empty file. On your workstation, do:



```
touch memberlist
svn add memberlist
```

`svn add` tells subversion to now keep track of the newly created file. Otherwise it would disregard it. Still on the workstation, do:

```
svn ci -m "added memberlist -authorname"
```

`svn ci` officially commits your changes to the repository. The `-m` tag allows you to specify a message. Typically this will describe the change(s) made and it is common courtesy to end the message with the author's name. Normally this is not relevant because individual members would have individual accounts in a repository and this is evident when looking at a history of revisions, but here all group members are committing under the same SVN account *rss-student*. Out of courtesy, append your name to each commit message.

Now on the netbook, do:

```
cd ~/RSS-I-group
ls
```

You should see an empty directory.

Again on the netbook, do:

```
svn up
ls
```

`svn up` updates the current directory with the centralized SVN repository. You should now see the file appear. Each individual member of the group must now do the following on the workstation, where `Firstname` is your first name and `Lastname` is your last name:

```
echo "Firstname Lastname" >> memberlist
svn ci -m "Added my name! -Firstname Lastname"
```

When this is done, run the following on the netbook:

```
svn up
gedit memberlist &
svn log
```

When the file opens in `gedit`, verify that the names of all five members are present.

`svn log` displays past revisions and the attributed messages. This is a handy tool in case you need to see the most recent changes to the repository. You should see five recent revisions, corresponding to the addition of the name of each individual member.

If you want to explore additional SVN functions, type `svn help`, or `svn help func` to view specific arguments for a particular function `func`.

This concludes the SVN tutorial. Now back to the lab!

## 7 Motor Control JAVA source

On the workstation, one person should first update the source directory `~/RSS-I-pub/` by doing the following:

```
cd ~/RSS-I-pub
svn up
```

You will be asked a password for the account `rss-student`. This is the generic password, not the one for your group SVN repository.

Now the person should copy the MotorControl Lab java files (`*.java` and `build.xml`) from the `~/RSS-I-pub/labs/MotorControl` directory to your working copy of your group repository (`RSS-I-group`):

```
cd ~/RSS-I-group
svn export ~/RSS-I-pub/labs/MotorControl/
svn add MotorControl
svn export ~/RSS-I-pub/labs/Chassis/
svn add Chassis
svn export ~/RSS-I-pub/labs/uORCInterface.jar
svn add uORCInterface.jar
svn commit -m "added new source"
```

Before continuing, familiarize yourself with the Java source in `MotorControl/src/`. Read and understand the classes along with their individual fields and methods. Refer to the motor control system overview diagram (Figure 11). IT IS HIGHLY RECOMMENDED THAT YOU DO THIS BEFORE STARTING THE REST OF THE LAB. If you understand the structure, your life will be much easier.

## 8 Characterize the encoder

1. Plug in the ethernet cable between the  $\mu$ Orc and the ethernet port on your laptop.

Note 1: Working on the laptop may require you to update your team's svn repository there.

Note 2: The  $\mu$ Orc board will remove the default gateway associated with the wireless. If you are connected to the  $\mu$ Orc and need to view an outside website (e.g., via svn), you can add a default gateway with:

```
sudo route add default gw <router IP>.
```

For example, if you are connected to the wireless EECS-MTL-RLE, run:

```
sudo route add default gw 18.62.0.1
```

2. Next, we need to initiate the visualizer just as we did in the previous lab. Run

```
orcspy
```

Familiarize yourself with its graphical user interface (GUI). It should look like Figure 12. The `orcspy` executable is also available in your path.

3. Orcspy should already be displaying its interpretation of the encoders from the quad phase ports on the  $\mu$ Orc; make sure that you have both motor encoders plugged into the  $\mu$ Orc correctly.
4. As in the previous lab, the center channels are used for directly modulating the PWM of the motor ports. The window for the two encoder ports is in the lower left of the screen. Spin the motor shaft back and forth manually by grasping the wheel, and watch the encoder value change. Make a thin pencil mark on the wheel, and turn it as nearly as possible through one full revolution (calculate via experimentation). *How many ticks does the encoder report per shaft revolution?*
5. Next, calculate the expected ticks/states per revolution from the encoder and motor specification sheets (calculate via documentation). We are using the HEDS-9000 (A) optical encoder module. It is incorporated into the motor package so you cannot see it directly. Don't forget that the motor has a gearhead. *Show your calculations. How closely (to within what percentage) do they match?*
6. Measure the motor's maximum (unloaded) angular velocity by counting the number of rotations in a period of time. You can do this visually or by using the encoder output in `orcspy`. *What is that value?*
7. Add the constants `GEAR_RATIO`, `ENCODER_RESOLUTION`, `WHEEL_RADIUS_IN_M`, `TICKS_PER_REVOLUTION`, and `MAX_ANGULAR_VELOCITY` in the appropriately labelled sections of `WheelVelocityController.java` to reflect the information obtained above. Hint: `TICKS_PER_REVOLUTION` and `ENCODER_RESOLUTION` should have the same units, except that `TICKS_PER_REVOLUTION` contains the `GEAR_RATIO` term.

## MotorControl System Overview Diagram

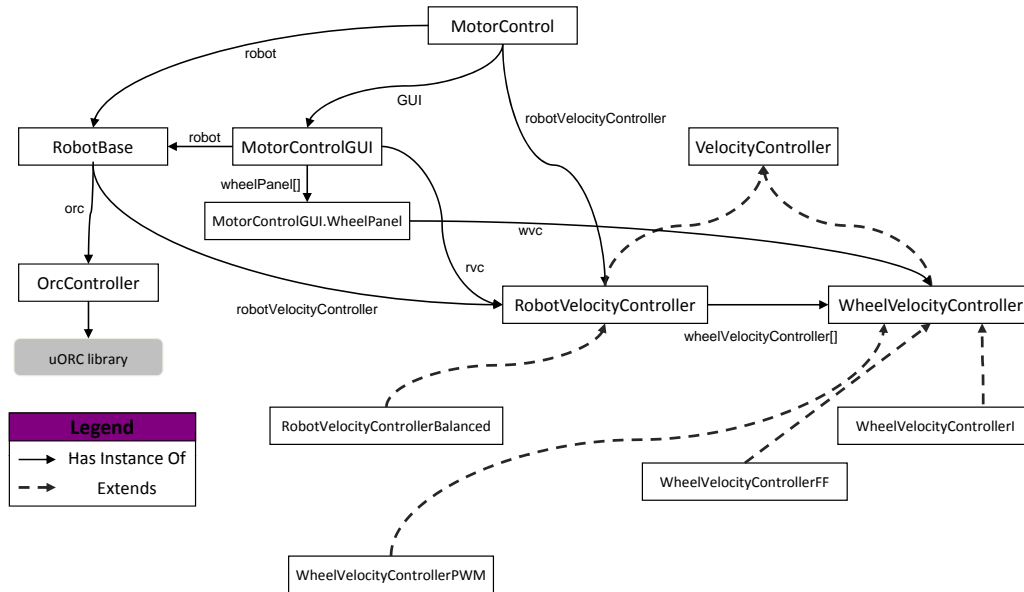


Figure 11: Solid lines and labels show dependency relationships between the classes used in this lab. For example, the main `MotorControl` class has a field `robot` of class `RobotBase`. Dashed lines show class inheritance relations (`is-subclass-of`) between various motor controllers used in the lab.

### 8. Derive the radians per tick from the ticks per revolution.

In `WheelVelocityController.java`, complete the implementations of:

```

computeRadiansPerTick();
computeEncoderInRadians();

```

See the method `update` in the superclass, `VelocityController`, and notice how subclass `WheelVelocityController` overrides it.

### 9. Derive an expression that converts from encoder ticks per second to motor rotational velocity in radians/second. The field `sampleTime` is updated in `VelocityController.update()` and holds the time, in seconds, since the last call to the control loop. Use this information to implement the `computeAngularVelocity()` and `computeTranslationalVelocity()` methods.

*Deliverables: Write up your answers to the questions above (8.4, 8.5, 8.6, 8.8) as part of your wiki materials. Comment your code, and commit your completed methods along with the confirming print statements you added.*

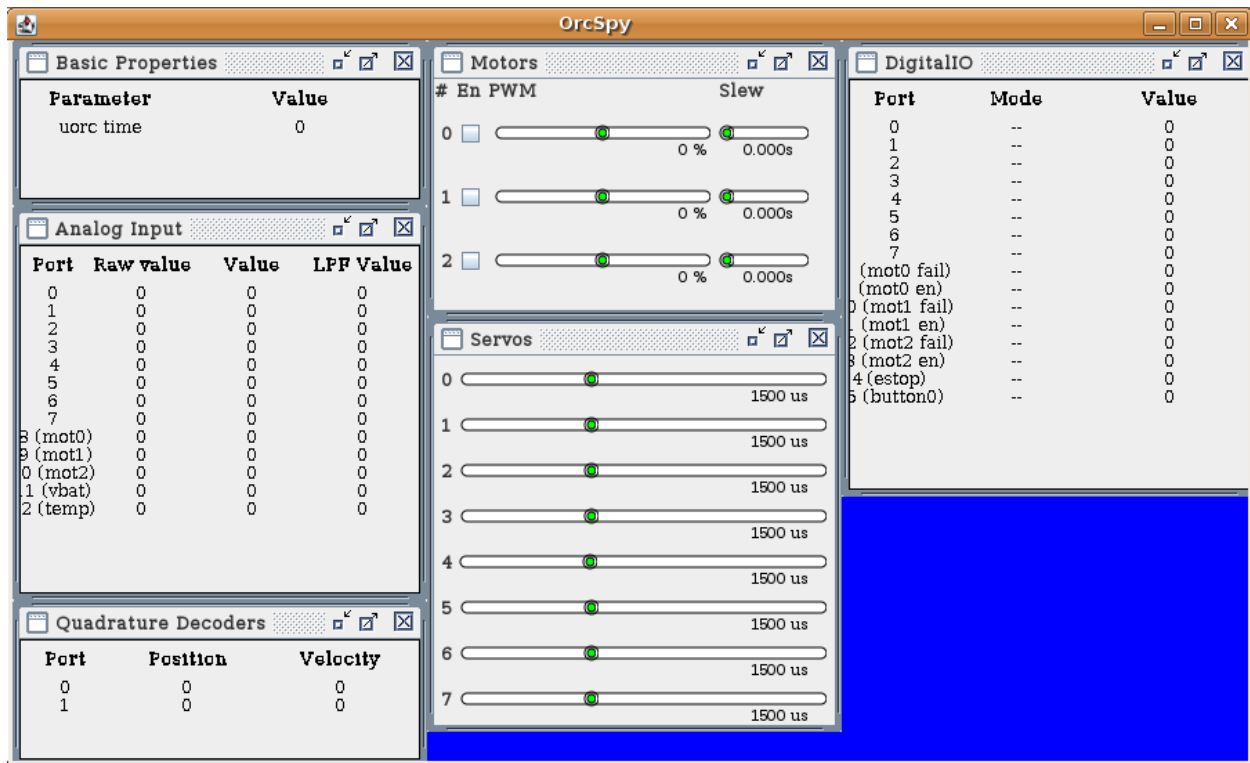


Figure 12: OrcSpy GUI

## 9 Motor Control

*If everything seems under control, you're just not going fast enough.*

— Mario Andretti

For each of the following sections, you will need to update the `MotorControl.java` file to call the appropriate type of Velocity Controller. While working through the following lab parts, you may wish to comment out the print statements you added in Part 8.

### 9.1 Direct PWM Control

1. You are now ready to actuate, i.e., control the motors via PWM, from the `MotorControlGUI` that is invoked by:

```
cd ~/RSS-I-group/MotorControl
ant
ant run
```

Note that there is a button set labelled “Input Function” that, at present, does not work when it is set to “Manual” and you move the “Desired” slider. Your goal is to make the “Desired” slider work properly. To do this, complete the implementation of `WheelVelocityControllerPWM.controlStep()`. This method should use the desired PWM value set for each motor in the `MotorControlGUI` class and write it to the appropriate field (instance variable) of the class `WheelVelocityController`.

If you then compile your updated source files via the commands above, you should be able to control the motor's PWM from the “Desired” slider. Press the “Start” button to control the robot. If the “Start” button is not visible, ensure that the `MotorControlGUI` is maximized.

2. You will create several logs using the “Start Log” button. Each start/stop pair creates a sequentially numbered file `dataPlotN.txt` in the current directory. An `ls -t` will display files sorted by creation time; use your editor or `more foo` to inspect the contents of the file “foo”. Verify that the log files contain data in the correct format by viewing the responsible print statements in `RobotBase.java`.

Now note the subdirectory `MotorControl/plots/`. Here you will find a utility script `makeplot` and a file `README.txt` explaining how to use it. Try generating a small log file from your java code, then run one of the `makeplot` examples in `README.txt` and view the resulting postscript plot.

You must copy or move your data files into `plots` (using `cp` or `mv` respectively) before invoking the plot generation scripts. Take care not to overwrite similarly-named files.

In `MotorControl/plots/`, use `gnuplot` to plot your logged data with staff-supplied plot parameters from file `Vel_PWM.gp`:

```
./makeplot Vel_PWM.gp (Your PWM data).txt (Your output file).ps
```

To view the resulting plot, use the command `gv foo.ps`, where `foo.ps` is the filename you provided to `makeplot`. Verify that the angular velocity tracks the PWM value, and that the velocity values seem reasonable given your observations of the motor’s physical behavior. After you get each plot working, use `svn` to add the plot data file and the generated plot to the repository.

## 9.2 Feed-Forward Velocity Control

Direct specification of PWM is not a very useful abstraction for controlling a single motor. It would be preferable to specify desired angular velocity. We will start by coding a linear feed-forward (i.e., no encoder sensing) angular velocity controller. (Such controllers are called “feed-forward” since they produce a behavior responsive to a control signal but with no dependence on how the system reacts to load.) To do this:

1. Compute the average angular velocity when PWM is at 100%. This provides a scaling factor to convert from desired angular velocity to commanded motor PWM. Through the GUI, experiment with different values of the scaling factor by changing the FF-gain.
2. Complete the `controlStep()` method for the `WheelVelocityControllerFF()` class, to implement an FF velocity controller using the `gain` variable inherited from the `WheelVelocityController` class. You will have to scale the desired velocity with the scaling factor you determined above to convert it to PWM. Test your controller through the GUI
3. Select the “Step” button. The “Desired” slider will disappear. Use the “Start Log” and “Stop” buttons to drive the **right** motor through a pre-programmed velocity range and log the results. Plot the test using `FFVel_Unloaded.gp`. Save the log file and plot to your `plots/` directory. *Include this plot, with a caption, in your wiki materials.*
4. Log another test, this time subjecting the wheel to variable loading with your hand. Plot this data with parameter file `FFVel_loaded.gp`. *Save and upload the plot as before. Compare the motor’s unloaded and loaded behaviors. Comment on the ability of the FF controller to track the desired angular velocity. On a mobile robot, When would an FF controller be useful? When would this type of controller fail?*

*Deliverables: Write up brief answers to the questions above and post plots to your wiki (you can use `ps2pdf` to convert your postscript plots to PDF, or screen-capture any display by pressing `ALT+PrtSc`). Add a comment line reading “Motion Control Lab, Part 9” to the top of any code block that you modified.*

## 10 Integral Motor Control

1. Complete the implementation of an integral gain feedback controller in method `WheelVelocityControllerI.controlStep()`. This method should scale the angular velocity error by the I-gain acquired from the Motor-Control GUI and accumulate it over time. Run the controller, using the “Desired” slider to command the setpoint. Observe the motor velocities that result. *What happens with a gain that is too low? Too high? Plot and save your*

experiments with the **right** motor to show that you effectively varied motor velocity, controller gain, and load. Use *makeplot* with the gnuplot script: `PVel_VariedGain.gp`. *Include the resulting plot(s) on the wiki.*

2. Tune your controller to be stable and sufficiently responsive for real-world use. Make it as responsive as you can. Choose the value you think is optimal for I-gain. Use the `Step` function in the GUI to characterize the controller's performance and *describe your controller's performance. If it performs poorly, why do you think this is so?*

Study the step-response of your controller, i.e., bring your motor up to maximum velocity, let it settle there, then command it to zero velocity with your controller. Depending on the I-gain value, there are six distinct convergence behaviors that your system will produce. They are:

1. Overdamped: The system converges, but does so slowly.
2. Critically Damped: The gain is just right; the system converges as fast as possible without going past the desired value (i.e., without overshoot).
3. Underdamped with Overshoot: The system overshoots, but corrects quickly.
4. Underdamped with Oscillation: The system overshoots, but corrects slowly. (This behavior is called "ringing.")
5. Oscillation - The system oscillates around the desired solution forever.
6. Instability - The system diverges from the desired solution.

*Vary the wheel gain slider to find the approximate gain regimes in which each behavior occurs. Sketch each behavior on sheet of paper. Photograph your sketches and post them on the wiki. Record the I-gain value or approximate range of values that produces each behavior. Across what time scale does the behavior occur in each case? Record this information on the wiki; it will come in handy when you design more complex controllers later in the class.*

*Deliverables: Add brief answers to these questions to the wiki. Commit your modified source files with descriptive comment lines reading "Motor Control Lab, Part 10" as above.*

## 11 Controlling Two Wheels

Consider how to coordinate both motors so that the robot drives in a straight line, so that the velocities at the rim of each wheel are equal. Under our earlier-stated assumption that the wheels have equal radii, this requires making both wheel motors turn at the same angular velocity. Moreover, our controller should do the right thing even when the motors are subjected to varying loads. Think about the two things your controller is trying to effect simultaneously: (1) each motor runs its wheel at (or near) the commanded speed; (2) both wheels propel the robot along at the speed. *Can both of these conditions always be met at the same time? In particular, think about how a large load on either or both motors must be handled by your controller.* There are four cases: (A) both motors unloaded; (B) left loaded, right unloaded; (C) left unloaded, right loaded; and (D) both loaded. *Briefly describe what your controller must do in each case. Is such a controller linear? Why or why not?*

Your two-wheel controller would consist at the lowest level of two integral angular velocity controllers you developed in Section 10 (scaled to wheel rim velocity), with one controller designated for the left wheel and the other controller for the right wheel. It would use the output of these controllers as feedback to a higher-level controller that deals with steady state error in terms of the difference in wheel speeds. The higher-level controller should use *proportional control* with a gain term multiplying the summed difference in wheel speeds.

Next, consider how to make the robot drive in an arc, rotate in place, or translate perpendicular to its wheel axis. Turning requires the desired speed of each wheel to differ. For example, if you command more speed from the right motor, you would expect the robot to turn to the left. Two-wheel speed control with an offset effectively allows the robot to do this. The lab staff can help you develop a block diagram of the desired controller and you have been given well-documented software which indicates where you need to add code to implement one.

Implement this feedback controller by completing the `controlStep()` method in `RobotVelocityControllerBalanced.java`.

Briefly describe your efforts on the wiki. Here are some steps to follow:

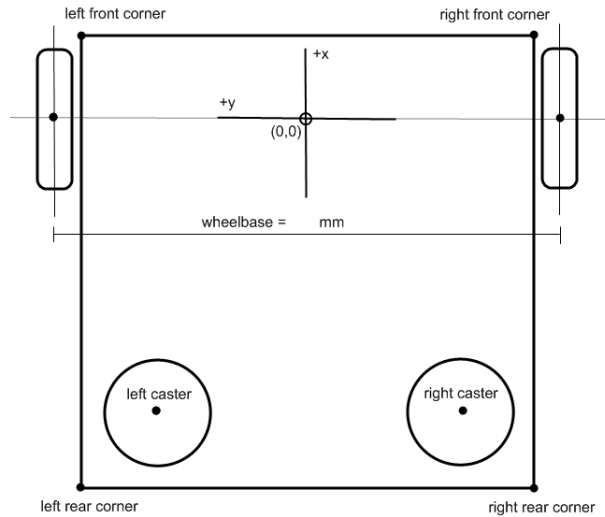


Figure 13: Robot body coordinates.

Generate a plot of the speeds of both motors, and the differential error, while heavily loading first one wheel, then the other. This plot uses parameter file `DError_Loaded.gp`. What are the corner cases? Does your code handle them elegantly?

*Checkoff: Demonstrate your working feedback controllers to the LA's before continuing.*

## 12 Establish Body and World Coordinates

You will now start tracking the robot's motion. To do so, you will first need to establish a 2D "body coordinate frame" for your robot. This frame should have its origin  $O = (0, 0)$  at the ground point directly below the midpoint of the robot's drive wheel axis. Your frame should be right-handed, with unit vectors  $\hat{x}$  pointing toward the front of the robot and  $\hat{y}$  pointing to the left as the robot is viewed from behind. Carefully mark  $O$  and (the directions of)  $\hat{x}$  and  $\hat{y}$  on your robot chassis with masking tape and a sharpie.

Measure and record the positions, in body coordinates, of the two drive-wheel ground contact points, the two caster wheel contact points, and the four corners of the robot's chassis. Make a sketch the robot frame, wheels, motors and casters with each of these points  $(x, y)_b$  labeled in the body frame. You will use this information later in the lab to recover the robot's actual displacement and orientation, or "pose"  $(x, y, \theta)_w$  in world coordinates.

Mark a two-meter square on the floor in masking tape (or share with another team). This will be the robot's "world coordinates". Take care to make your right angles true, by checking that the square's diagonals have equal length. Subdivide the square into four one-meter squares.

*Deliverables: Post a diagram of your robot to the Wiki. The diagram should include positions, in body coordinates, of all the components mentioned above.*

## 13 Translate a Specified Distance

Fill in the `translate` method in `Chassis/RobotPositionController.java` to command your robot to move forward or backward at a specified constant velocity for a specified distance in meters, relative to its current pose. *Document your code with comments as you work.* Remember that this velocity is a *linear* measure with units in `m/s` (versus rotational velocity with units of `radians/s`). You may choose to implement either *feed-forward*

or *feedback* control. In any case, your implementation of `translate` should *block*, i.e. it should not return until the translation is considered complete or an un-recoverable error has occurred. The robot should not be moving after `translate` returns.

1. The velocity controller developed previously expects to see angular velocity of the wheel. Define a constant that converts linear translational velocity of the wheel on the ground to the equivalent (wheel) angular velocity. It should use the wheel circumference, which you measured above.
2. The (signed) number of encoder ticks which have occurred since your program started running will be available in instance variables (read the code to find them). Define another constant that converts ticks to linear translation in meters.
3. It should be possible to implement feed-forward control entirely within the `translate` method. To implement closed-loop control, you will probably want to write code both in the `translate` and `controlStep` methods. Note that `controlStep` and `update` are both called from the control loop thread for your robot (defined in `RobotBase.java`), and that this is a different thread than the one that calls `translate`. Since states, like encoder tick variables, can be accessed from both threads, you will likely need to use the `synchronized` keyword to reliably read and write states. The `synchronized` keyword locks a method, allowing only one thread at a time to access it.
4. It is up to you to define what it means for the motion to have “completed” or “errored”. One way to do this is to define an error tolerance (in the appropriate units) for the robot position, and to periodically check that the robot is within tolerance of where you expect it to be. When you expect it to be in the goal position (i.e. the position it should have at the end of the translation) and your code concludes that it is indeed within the defined tolerance of that position, you can consider the motion complete.
5. Wheel slip (e.g. skidding) introduces odometry errors (why?). If the wheels slip, the robot’s motions will be less accurate, and pose error will accumulate. To reduce wheel slip, you can limit the robot’s acceleration. One way to do this is to drive very slowly; a preferable way is to explicitly ramp up the commanded speed, over a specified distance, at the start of each motion, and then ramp down the commanded speed at the end of the motion.
6. Having the right parameter values (e.g. control gains) makes the difference between a solution that works great and solution that doesn’t work at all. Finding the right parameter values can be hard work. You can make this job much easier by building a user interface for adjusting parameters and viewing the internal state of your solution. You can see how to do this by examining the source code for the `MotorControlGUI` and `OrcSpy` applications.
7. To measure the actual pose, consider the body frame you established earlier, and work out how a triplet of numbers  $(x, y, \theta)_w$  describes the robot’s pose (position and orientation) in world coordinates. Given two measured points  $(x_L, y_L)_w$  and  $(x_R, y_R)_w$  describing the robot’s left-wheel and right-wheel ground contacts, respectively, write expressions for the three components of the robot’s absolute pose in world coordinates, i.e.:

$$\begin{aligned}x_w &= x(x_L, y_L, x_R, y_R) \\y_w &= y(x_L, y_L, x_R, y_R) \\\theta_w &= \theta(x_L, y_L, x_R, y_R)\end{aligned}$$

8. Place your robot so that its initial pose  $(x, y, \theta)_w$  is  $(0, 0, 0)$  with respect to marked lab coordinates. Using calls to `translate` at the indicated place in `Chassis.java`, issue a series of translation commands varying in sign, duration and speed. (You may want to adjust the controller gains, which are set by code in that file). *Measure the robot’s actual final pose  $x, y, \theta$  (translation and orientation) in world coordinates. Plot the your relative (%) error for 3 trials using `gnuplot`. Explain any significant errors.*

**Hint** Log your hand-measured  $(x_L, y_L, x_R, y_R)$  values to an ascii file. You may use whatever software you like to produce three error vs. trial number plots. If using `gnuplot`, write `gnuplot` expressions to compute  $x_w, y_w,$  and  $\theta_w$  from each data entry. The differential error `gnuplot` file from the Motor Control Lab shows how to express algebraic expressions in `gnuplot`; the terms \$5 and \$4 in the “plot” command refer to the fifth and fourth column of `data.txt`, respectively. Add the line `set angles radians` somewhere above your plot



command, and use the built-in gnuplot function `atan2` (google gnuplot atan2 for more info). Note that the backslashes in the `plot` command are required when splitting plot descriptors across multiple lines.

*Deliverables: Post any plots and explanations on the wiki, with a brief discussion of the procedure you followed. Document and commit your java code and any gnuplot scripts you wrote or used. Be prepared to demonstrate your robot's motion in lab.*

## 14 Rotating in Place

1. Fill in the `rotate` method in `RobotPositionController.java` to rotate your robot about its origin at a specified speed, relative to its current pose. Think about how to implement counter-clockwise and clockwise rotation commands, using your knowledge of the wheelbase and wheel radii. As with `translate`, `rotate` should block until the motion has completed or errored, and the robot should not be moving after it returns. Again, you may implement either feed-forward or feedback control.

**Hint** Convert the desired robot rotation speed to a desired linear or angular speed for each wheel, and the desired robot rotation angle to a linear or angular distance for each wheel.

2. By analogy to Part 13, measure the robot's actual final pose in world coordinates for a series of three commanded rotations differing in sign, duration and speed. (Include at least one turn of  $\pi$  or more radians.) *Plot the your relative (%) error for 3 trials using gnuplot. Report any undesired translations and/or rotations and try to explain them.*

*Deliverables: Include a brief discussion of your procedure on the wiki, along with any plots and error explanations. Document and commit your java code and any gnuplot scripts you wrote or used. Be prepared to demonstrate your robot's motion in lab.*

## 15 Driving Out and Back: Error Upon Return

*Few can foresee whither their road will lead them, until they come to its end.*

— J.R.R. Tolkien, *The Lord of the Rings*

1. Write code in `Chassis.java` to command your robot to drive “out and back:” roll straight one meter ahead, rotate  $\pi$  radians, roll straight one meter ahead, and rotate  $-\pi$  radians. In other words, the robot should take a two-meter excursion, returning to its starting pose. You can specify the speed at which, or time duration over which, your robot should execute this excursion. (Try a few different values.)
2. Before running your method, use your results from Part 13 and Part 14 above to predict what your sensed and measured final poses will be after execution. *Post your predictions on the wiki.* Now execute your program and measure the resulting pose. *How close are your predictions to reality?*

*Deliverables: Include your answers to questions above, explanations, and a brief discussion of your procedure in your lab report. Be prepared to demonstrate your work in lab on the due date marked at the top of this document.*

## 16 Driving in a Square: Error Upon Return

1. Write code in `Chassis.java` to command your robot to drive around a square with one-meter side-length. Experiment with a variety of commanded translation and rotation speeds.
2. *Predict and measure the robot's final pose as above.* Record your results. *How reliably does your robot return to its starting position and orientation?*
3. Use the RSS video camera (or your own) to capture a short video of your robot's excursion (max size 10MB or as directed by lab staff).

*Deliverables: Discuss your robot's performance. Post your video. Be prepared to demonstrate your work in lab on the due date marked at the top of this document. Also, be sure to `svn commit` your modified source files into your group's repository with the descriptive comment "Motion Control Lab, Part 16."*

## Wiki Materials

Check that you have posted to the wiki:

- Any notable procedures you employed;
- A brief description of any major code edits;
- Plots for §9 through 11 and explanation for errors.
- Discussions of pose errors for §13, 14, 15, and 16.

## Briefings

You may brief whatever you feel is relevant; these are merely suggestions.

- A brief description of what you did, as individuals and as a team;
- Brief video of your differential controller working;
- Brief video of your robot driving in a square;
- Plots from a salient subset of your experiments;
- Any issues and how you dealt with them;
- Time spent individually and as a team; and
- Any suggestions for improving the lab next year.

*Post your briefing on the wiki.*

Your committed code and Wiki materials (with your brief responses to the lab questions, as well as your images, plots, and videos) are due on the date/time marked at the top of this handout. To submit your software for grading, commit all files into your group's repository under a top-level directory named "MotionControl". Make sure that a fresh checkout, which the staff will perform, reproduces your code in its entirety.

**Wiki Avatar Updates:** After preparing all the hand-in materials, return to your team's Wiki Avatars. Each of you should tally your total effort there, including time spent writing up your report, under your Saved Progress section. Additionally, be sure to answer the proficiency questions again **as of the end of the lab**, and place your self-assessments into the "End of Lab" portion of the lab 2 section.

**This concludes the Motor Control Lab.**