Dynamic Tracking with AprilTags for Robotic Education
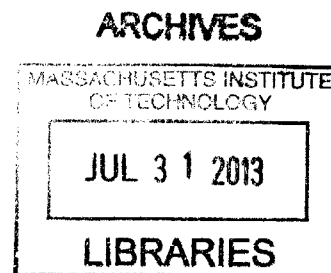
by

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Abstract

This thesis describes and portrays the use of AprilTags, 2D tools used for the identification of locations in 3D space, to control the position and angular velocity of a rotating object by way of a PD controller. This project also sought to determine the upper limits of the usefulness of AprilTags while on moving objects, that is, the highest velocities at which AprilTags can be detected by a low-cost USB camera. The resulting project may be used for a classroom demonstration, which shows how AprilTags may be used as a means of sensing. When effective, AprilTags can be used to measure the position and angle of an object or location, and they are much more inexpensive than alternative solutions, for example, encoders.

Thesis Supervisor: Dr. John J. Leonard
Title: Professor of Mechanical and Ocean Engineering

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Contents

Chapter 1

Introduction

This thesis project seeks to explore the functionality of AprilTags in dynamic applications through the observation of an AprilTag attached to a wheel moving at a fixed velocity.

1.1 Objectives

The main objective of this thesis project was to use AprilTags, a 2-dimensional tool used for recognition and localization, and a low-cost camera to measure the position and velocity of moving objects. AprilTags are often used in still images or during slow movement, and this thesis project sought to explore how well AprilTags could be recognized at higher velocities using low-cost equipment. Understanding how well AprilTags could be recognized during dynamic applications could lead to further work, possibly involving closed loop feedback control.

1.2 Motivation

1.2.1 Exploring the Robustness of the AprilTags System

AprilTags are extremely useful tools for recognition and localization of features in 3-dimensional space. AprilTags are easily recognized even when slightly warped, tilted, or small due to the robust recognition system developed by Professor Edward Olson at the University of Michigan [6]. Because of this, they could perhaps be used for other interesting uses, even those that would cause some distortion of the AprilTags. [5]

Uses that would cause different extents of distortion of the AprilTags would be those involving some amount of movement. Many cameras, including inexpensive ones, such as webcams, capture images by 'reading' their pixels line by line. As a result, a captured image would contain lines of pixels from different points in time, and it would be distorted; the higher the velocity of the moving object during image capture, the more distorted the resultant image. Since the AprilTags system is robust to some amount of distortion [6], it would be interesting to determine the extent of this robustness; that is, how quickly AprilTags can be moving and still be recognized. There are many factors that affect this, such as gain and exposure, and the effects of these factors were explored in this project. [2]

1.2.2 Cost Effective Alternatives to Encoders

Another motivation for this thesis project was the possibility of determining a more cost effective way of measuring position and velocity. High quality encoders can be very expensive so using AprilTags to perform a similar function could be very useful, particularly for classroom applications where cost may be a hindrance. This setup may also be used for a classroom demonstration, which displays and explains how AprilTags may be used. [5]

1.2.3 Personal Motivation

As a personal motivation, this project was an interesting introduction to the realm of 3-dimensional mapping. Having been very interested in 3-dimensional mapping in the past, as well as the capabilities of simultaneous localization and mapping (SLAM), AprilTags seemed to be an engaging way to explore even just the surface of the subject.

1.3 Experimental Setup

1.3.1 Equipment for Tracking AprilTag

In order to track a moving AprilTag within a confined space, so that it could be used in something like a classroom demonstration, a small tag of side length 3 inches was was attached to a wheel of diameter 11.8 inches. The wheel was laser cut from colorless cast acrylic of 1/8 inch thickness. Thin acrylic with large cutouts was used in order to minimize the torque required from the DC motor. Ultimately, smooth rotation could not be achieved due to the vertical shear force on the shaft of the motor due to gravity, but this discontinuity was less pronounced at higher angular velocities.

The Logitech Webcam C250 was used to capture the dynamic image of the AprilTag on the wheel. It was mounted on a Vista Explorer Tripod in order to remain stationary during different cycles of data collection.

1.3.2 Electronics

Motor commands were set in the Arduino program, which was then uploaded via serial port to an Arduino Mega. These commands were transmitted to the DC motor attached to the wheel via the motor controller. The motor chosen was the Pololu

metal gear motor, which had a gear ratio of 131:1 and 64 counts per revolution (CPR) on the motor shaft. As a result, there would be a resolution of 8400 CPR on the output shaft of the gearbox. This resolution would be sufficient for cross-checking the angular velocities measuring using the AprilTags system.
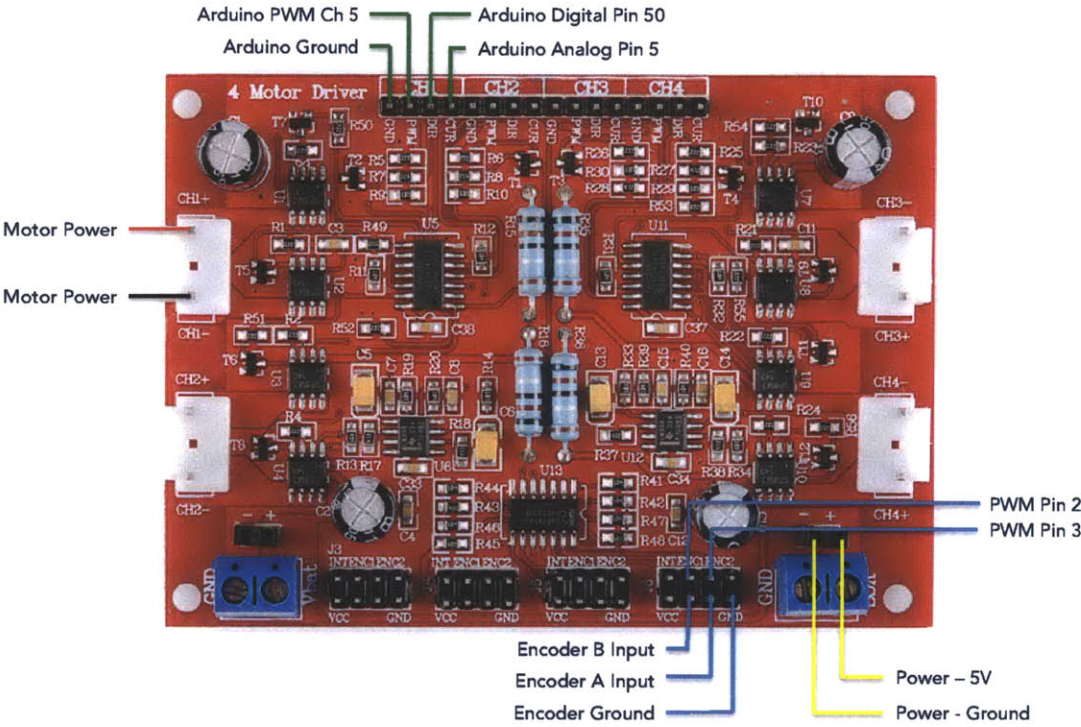

Figure 1-1: Rover 5 Motor Driver Board Showing Connections
(Source of Image of Board: www.littlebirdelectronics.com)

Since the motor required 12 V, a separate power supply (Mastech HY3005D DC power supply) had to be used in order to power both the motor and the Arduino. The Rover 5 Motor Driver Board, which is shown above in Figure 1-1 with its connections, was used to control the DC motor.

Chapter 2

AprilTags

2.1 Summary of AprilTags

AprilTags are system of 2-dimensional codes, like Quick Response (QR) Codes, that are used for localizing features. Whereas QR Codes may contain hundreds of bytes of information [7] and require alignment with the camera by the user [6], AprilTags have a very small payload of just several bits and can be recognized when only in a small part of the image, tilted, or partially obscured due to the quick and robust line detection system of AprilTags, which allows for easy location of the AprilTag. The AprilTag system is similar in functionality to ARTags, another tag system used to localize features, but AprilTags were the better choice since the AprilTags system is public and very well documented. AprilTags are often used as visual fiducials: artificial features used to distinguish different regions of a surface from others. In addition to recognizing the AprilTag and therefore the feature, the system is used to obtain the position and orientation of the AprilTag, thus allowing for full six-degrees-of-freedom localization. [6]

The AprilTags algorithm works by finding the magnitude and gradient of each captured image at every pixel; clusters of pixels of similar gradient and magnitude are joined together using a least squares method to create the edges of the AprilTag after
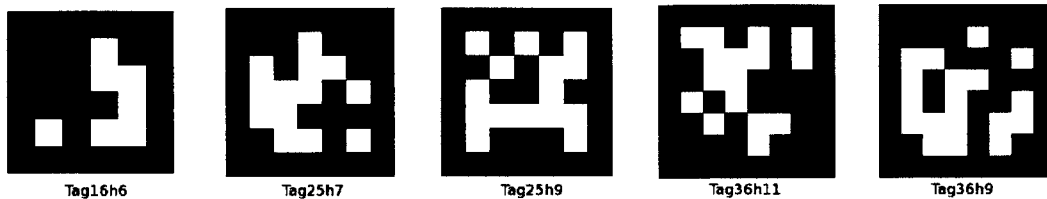
Figure 2-1: Examples from Different Families of AprilTags
(Source: http://people.csail.mit.edu/kaess/apriltags/)

noise is eliminated using a low pass filter. [6] Afterwards, if the correct tag family is specified in the algorithm, the tag is recognized and the coordinates of the center of the AprilTag and its orientation of the tag are returned. Examples from the different AprilTag families are shown above in Figure 2-1. The AprilTags program returns a rotation matrix [2], which contains information about the position and orientation of the AprilTag relative to the position of the camera. The AprilTags program that was used for this thesis project was based on the program written by Dr. Michael Kaess. Kaess' program returns a rotation matrix to the terminal that can be used to obtain the x-, y-, and z-coordinates of the AprilTag relative to the camera, as well as the distance from the center of the tag to the origin at the camera. [3]

2.2   Uses of AprilTags

AprilTags are useful for generating maps of 3-dimensional surfaces. For example, in current 3-dimensional mapping of ship hulls, artifacts, such as the results of biofouling, are used by a moving underwater vehicle with some sort of camera to differentiate parts of the ship hull from each other. These artifacts are used by these vehicles in a process known as simultaneous localization and mapping (SLAM), which enables the generation of the map. Without these artifacts on the hull, 3-dimensional mapping becomes much more difficult; this is where AprilTags become very useful. In the event that a ship hull has little to no biofouling, there must be other means of differentiating the different parts of the ship. AprilTags can then be used to distinguish particular regions. [1]

This application is useful for many purposes. With the use of AprilTags, an underwater vehicle may create a map of a ship hull, which may be used to inspect it for fractures and other hazards such as explosives. [1] Therefore mapping is also important for safety as it removes the requirement that these ship hulls be inspected by human divers. SLAM, and therefore the use of these tags, is also important in the development of 3-dimensional maps that may be used by self-driving cars. [5] The more precise the process is, the safer this possibility becomes.

Chapter 3

Software
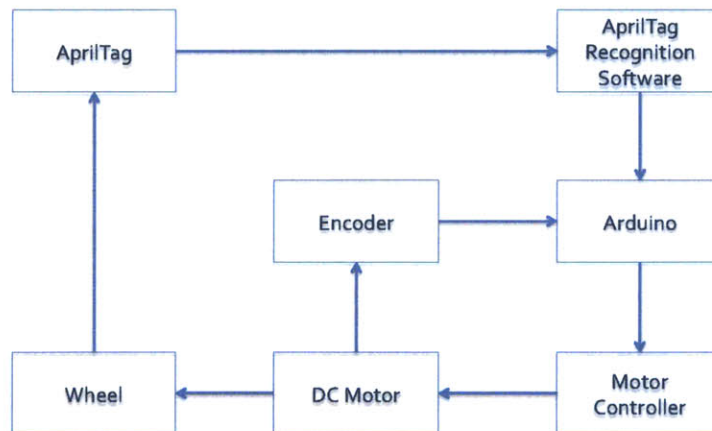
3.1 AprilTags Software

Figure 3-1: Interactions Between Components Used for AprilTag Tracking

The incorporation of the the AprilTags recognition software into the experimental method is shown in Figure 3-1.

3.1.1 Preexisting Software

The program used for this thesis was generated by modifying the AprilTags recognizing program written by Dr. Michael Kaess. The following functionalities of Kaess' program were utilized [3]:

1. Recognizes one or more AprilTags in a captured image.

2. Determines the distance between the center of the AprilTag and the origin at the camera.

3. Determines the x-, y- , and z-coordinates of the center of the AprilTag with respect to the center of the camera.

4. Sends a string to a specified serial port. This functionality is used to communicate commands to an Arduino, which is then used with the motor controller to control the DC motor.

3.1.2 Modifications made to Existing Program

Dr. Kaess' program was modified so that it would additionally be able to:

1. Calculate the angular velocity of a rotating object with an attached AprilTag. This was done by setting up the camera so that it could capture the image of the wheel with the attached AprilTag. The measured coordinates that were recorded by the AprilTags program were observed, and a small range of y- and z-coordinates through which the AprilTag passed once per revolution was selected. Using the *ctime* C++ library, the timestamps at which the AprilTags passed through this range (t_1 and t_2, both in seconds) were used to calculate the RPM of the system as follows:

$$\text{RPM} = \frac{60}{t_2 - t_1} \tag{3.1}$$

where t_2 is the most recent time at which the AprilTag was within a specified range, and t_1 is the time at which the AprilTag was in the specified range right before that.

2. Use Dr. Kaess' serial communications library to send information to the serial port for eventual communication with the Arduino for controlling the motor.

3. Implement proportional-derivative controllers that could be used to control either the position of the AprilTag - the angle through which the wheel has turned - or the angular velocity of the wheel.

3.2   Arduino Software

The Arduino program was used to control the angular velocity of the motor shaft, and therefore the angular velocity of the wheel and the velocity of the AprilTag attached to it. To control the position or velocity of the AprilTag via closed loop feedback, the Arduino program would read in a string from the AprilTags recognition software via the serial port, parse it and save the value obtained as a variable within the Arduino sketch. The string would contain a command that would be sent to the Rover 5 Motor Driver to control the velocity command sent to the motor. This command would be the result of the proportional-derivative controller within the AprilTags recognition program.

Chapter 4

Experiments

4.1 Measuring Angular Velocity Using AprilTags

4.1.1 Experimental Setup

The experimental setup used for this thesis project is shown in Figure 4-1 on the following page. The wheel, which was laser cut from 1/8 inch thick colorless acrylic, was fixed with two 4-40 screws to an aluminum mounting hub made by Pololu. The mounting hub was fixed to the shaft of the motor using a set screw. The AprilTag, which was from the 25h9 family, was fixed between the wheel and a 4-by-4 inch square of 1/8 inch thick colorless acrylic, which was bolted to the wheel.

A Logitech Webcam C250 was used to capture images during the dynamic measurement of the angular velocity of the wheel. The camera was mounted on a Vista Explorer tripod, also shown on the following page in Figure 4-2 so that the coordinate frame was not shifted during data collection.
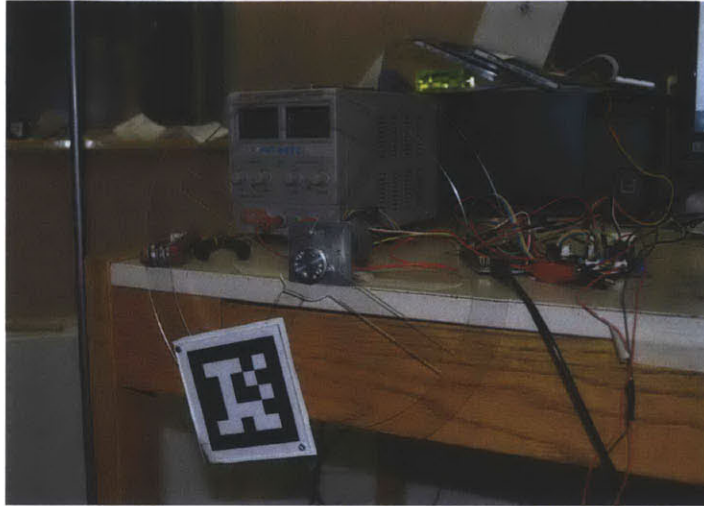
Figure 4-1: 25h9 AprilTag Mounted onto Colorless Acrylic Wheel

Figure 4-2: Logitech Webcam C250 Mounted on Vista Explorer Tripod

4.1.2 Measuring the Angular Velocity

The angular velocity of the wheel was measured using the method described by Equation 3.1. For each command specified using the Arduino software, approximately 30 different readings were recorded. For each different speed specified using the Arduino software, the specified range through which the AprilTag had to pass so that the time, t_1 or t_2, would be recorded had to be modified. First, the AprilTags program was allowed to run as the wheel was turning, and the y- and z-ranges were observed. After that, the range was modified such that the AprilTag would pass through it a maximum of one time per revolution.

To cross-check the angular velocities measured by the AprilTags system, the average angular velocity of the motor shaft could also be calculated using the motor's encoder by using the following equation:

$$\omega_{avg} = \frac{1}{n} \sum_{i=1}^{n} \frac{\Delta \Theta}{\Delta t} = \frac{1}{8400} \frac{enc_{n+1} - enc_n}{t_{n+1} - t_n} \tag{4.1}$$

where ω_{avg} is the average angular velocity of the motor's shaft, n is the number of AprilTag readings carried out by the AprilTags program during the data collection period, Θ is the angle of the motor's shaft, t is time in minutes, and 8400 counts per revolution is the resolution of the encoder.

Since a range was used, the RPM measured may have been incorrect. A specific value could not have been employed, because of the frame rate of the camera when used with the AprilTags system. The frame rate was on average 9 or fewer frames per second; therefore, the system only returned the coordinates of a select number of positions per rotation of the wheel. Therefore, even if the angular velocity of the wheel were perfectly constant - which it was not because of the asymmetry of the structure used to support the AprilTag - it is likely that the AprilTags system would still provide inaccurate readings.

4.2   Issues Encountered During Data Collection

1. Motion blur is one of the biggest issues in tracking moving AprilTags. If the velocity of the AprilTag exceeds the frame rate at which images are recorded and processed, the image appears blurred or distorted. The webcam used, like most low cost cameras, reads in image data one row of pixels at a time. Since the tag is constantly moving during data (image) collection, the rows of the detected image will actually be from different points in time; this results in a distorted, specifically slanted image. Decreasing the exposure time reduces this kind of distortion but also results in a darker image. The image can be brightened once more by increasing the gain, but this also amplifies artifacts and can therefore result in a very noisy image. [2]

2. Because the region of the tag closer to the circumference of the record player has a higher velocity than the region of the tag near the center of the wheel, the image appears distorted. That is, the outer region appears to be smaller than the inner region.

3. The AprilTag was held flat using a 1/8 inch thick square of colorless acrylic. The layer of plastic above the AprilTag causes some distortion due to light refraction, but this did not seem to affect the results significantly.

4. When decreasing the exposure of the image, the effect of the room light flickering at approximately 60 Hz [4] is amplified. Since the image is read line by line, there are light and dark strips on the detected image. If the exposure is too low, the dark strips are nearly black, which causes problems in reading the AprilTag. This problem may be circumvented by turning off all fluorescent lighting and using incandescent bulbs for illumination instead. [2]

Chapter 5

Results of Angular Velocity Measurements

Approximately 30 angular velocity measurements were recorded for each motor speed specified in the Arduino program. The results of these measurements are shown in Figure 5-1.

From Figure 5-1, a clear linear relationship can be seen between the uppermost clusters of data points and the velocity commanded to the motor from the Arduino. This means that to some extent, the AprilTags software may reliably measure the angular velocity of the wheel. To check the accuracy of these uppermost readings, the data would have to be compared to measurements made by the encoder. In this thesis, this small uppermost range will be referred to as the 'actual' angular velocity of the wheel.

The existence of the lower angular velocities can be explained by the method used to measure the angular velocity in the AprilTags system. Since the range was chosen such that the AprilTag would pass through it a maximum of one time per revolution, there were often revolutions during which the AprilTag was not recognized at all. This was because no detections were made by the recognition software within the predetermined range during that rotation of the wheel. Therefore, as can be seen in

Figure 5-1, there are many data points at values that are a fraction of the expected result. This is due to the difference in time between two times the that system detected a tag within the specified range being a multiple of the actual period of rotation.
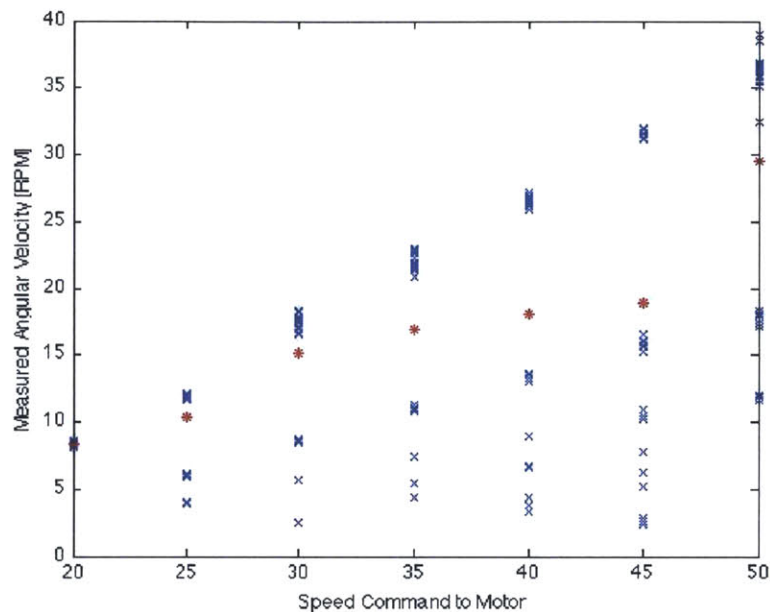

Figure 5-1: Angular Velocity Measurements as Determined by the AprilTags System

The red points in Figure 5-1 show the average angular velocity measured by the AprilTags system at each angular velocity commanded by the Arduino program. In general, the red points deviate lower and lower from the 'actual' angular velocity of the wheel, likely due to a higher frequency of the AprilTag not being recognized in the predetermined range in a rotation of the wheel. This is probably a result of a combination of motion blur and the insufficiently high frame rate of the camera.

At the speed of 50, as commanded by the Arduino program, the average is closer to the 'actual' angular velocity. This is probably due to the fact that the range of y- and z-coordinates had to be increased significantly so that the tag would be recognized in a significant number of rotations of the wheel during the period of data collection. It is expected that at a sufficiently high velocity, this method of measuring the angular

velocity of the wheel would no longer be effective.

Chapter 6

Future Work: Implementing Controllers

An interesting dynamic application of AprilTags would be in executing closed-loop feedback, that is, using the current state of the system to achieve a desired state. This chapter explores how a position and velocity controller would be implemented. As seen from the results shown in this thesis project, the AprilTags recognition software works best at lower velocities. These controllers were not implemented due to issues with serial communication between the AprilTags program and the Arduino.

6.1 Position Controller

The position controller could be implemented using a simple proportional-derivative controller. First, an AprilTag would have to be centered on the axis of the wheel and its coordinates with respect to the camera recorded. The AprilTags program would then read in the y-coordinate of an AprilTag position along the circumference of the wheel and use it to calculate the angle as follows:

$$\Theta_{curr} = \arcsin \frac{y_{AprilTag} - y_{center}}{r} \tag{6.1}$$

where r is the distance between the center of the wheel and the center of the AprilTag on the circumference of the wheel, and Θ_{curr} is the current angle when measured as shown below in Figure 6-1.
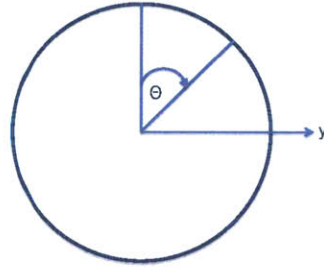

Figure 6-1: Definition of Angle

This would be used along with Θ_{des}, which is the desired angle of the wheel, to calculate the command, C_{pos}, which would be sent via serial port to the Arduino where it would be passed to the motor controller and thus the motor turning the wheel. This simple proportional-derivative controller is shown below in Equation 6.2.

$$C_{pos} = k_{1,pos}(\Theta_{des} - \Theta_{curr}) - k_{2,pos}\dot{\Theta} \tag{6.2}$$

where $\dot{\Theta}$ can be approximated as

$$\dot{\Theta} \approx \frac{\Theta_{curr} - \Theta_{prev}}{\Delta t} \tag{6.3}$$

where Θ_{prev} is the angle of the wheel during the immediately previous loop of the AprilTags program, and Δt is the time difference between the time at which Θ_{prev} was measured and the current time. The gains, $k_{1,pos}$ and $k_{2,pos}$, would be tuned experimentally.

6.2   Velocity Controller

The implementation of the velocity controller would be in some ways similar to the implementation of the position controller. One difference is that the y- and z-axes would not have to be centered at the axis of the wheel since the angle of the AprilTag is not particularly important. [2] Once again, a simple proportional-derivative controller would be used and the command C_{vel} that would be sent via serial port to the Arduino would be calculated as follows:

$$C_{vel} = k_{1,vel}(\omega_{des} - \omega_{curr}) - k_{2,vel}\dot{\omega} \tag{6.4}$$

where $\dot{\omega}$ can be approximated as

$$\dot{\omega} \approx \frac{\omega_{curr} - \omega_{prev}}{\Delta t} \tag{6.5}$$

where ω_{prev} is the angular velocity of the wheel during the immediately previous loop of the AprilTags program, and Δt is the difference between the time at which ω_{prev} was measured and the current time. The gains, $k_{1,vel}$ and $k_{2,vel}$, would be tuned experimentally.

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